NASA CR151970

PARAMETRIC STUDY OF TRANSPORT AIRCRAFT SYSTEMS COST AND WEIGHT

BY

SCIENCE APPLICATIONS, INC.

MICHAEL N. BELTRAMO

DONALD L. TRAPP

DOUGLAS AIRCRAFT COMPANY

BRUCE W. KIMOTO

DANIEL P. MARSH

APRIL 1977

(NASA-CR-151970) PARAMETRIC STUDY OF TRANSPORT AIRCRAFT SYSTEMS COST AND WEIGHT (Science Applications, Inc., Los Angeles, Calif.) 288 p HC A13/MF A01 CSCL 01C

N77-26106

Unclas

G3/03 29758

Prepared under Contract No. NAS2-8703
for the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER
MOFFETT FIELD, CALIFORNIA

SCIENCE APPLICATIONS, INC.
Economic Analysis Division
1801 Avenue of the Stars, Suite 1221
Los Angeles, California 90067
(213) 522-2681

NASA CR 151970

PARAMETRIC STUDY OF TRANSPORT AIRCRAFT SYSTEMS COST AND WEIGHT

BY

SCIENCE APPLICATIONS, INC.

MICHAEL N. BELTRAMO

DONALD L. TRAPP

DOUGLAS AIRCRAFT COMPANY

BRUCE W. KIMOTO

DANIEL P. MARSH

APRIL 1977

Prepared under Contract No. NAS2-8703
for the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER
MOFFETT FIELD, CALIFORNIA

SCIENCE APPLICATIONS, INC.
Economic Analysis Division
1801 Avenue of the Stars, Suite 1221
Los Angeles, California 90067
(213) 522-2681

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF TABLES

LIST OF TABLES (CONTINUED).......

LIST OF TABLES (CONTINUED)

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF ABBREVIATIONS

AC	Alternating Current
AGD	Axial Gear Differential
APU	Auxiliary Power Unit
AST(M)	Advanced STOL Transport (medium)
ATM	Air Turbine Motor
BPR	By Pass Ratio
CAC_{100}	Cumulative Average Cost for 100 Units
CER	Cost Estimating Relationship
CSD	Constant Speed Drive
DC	Direct Current
ECS	Environmental Control System
EPU	Emergency Power Unit
FAA	Federal Aviation Agency
GLA	Gust Load Alleviation
HP	Horse Power
HZ	Hertz
IDG	Integrated Drive Generator
IPS	Integrated Pneumatic System
MAC	Mean Aerodynamic Chord
MDAT	Medium Density Air Transport
MEW	Manufacturer's Empty Weight
MLA	Maneuver Load Alleviation
MUX	Multiplex
NASA	National Aeronautics and Space Administration
RSS	Reduced Static Stability
SCAT	Supersonic Cruise Air Transport
STOL	Short Takeoff and Landing
TOGW	Takeoff Gross Weight
TWA	Trans World Airlines
VSCF	Variable Speed Constant Frequency
WER	Weight Estimating Relationship

PREFACE

This report presents the results of a study to determine parametric cost and weight estimating relationships for commercial and military transport aircraft at the standard weight group or system level. The study was sponsored by the National Aeronautics and Space Administration under contract number NAS2-8703. Mr. Joseph L. Anderson monitored the study for the V/STOL Systems Technology Branch of the V/STOL Aircraft Technology Division, Ames Research Center. Work was performed between January 1975 and April 1977 by the Economic Analysis Division of Science Applications, Inc. and its subcontractor, The Douglas Aircraft Company.

The study effort reported herein is a continuation of work also sponsored by NASA under contract number NAS2-7836 which resulted in a report, Parametric Study of Transport Aircraft System Weight and Cost (R-1816, October 1974) by PRC Systems Science Company with The Douglas Aircraft Company and Lockheed California Company as subcontractors. The principal investigators for this previous report, which is referred to frequently in the present report, were Mr. Trapp and Mr. Marsh.

The two principal objectives of the present study effort were to refine the cost and weight estimating relationships developed in the previous report (with emphasis on the cost estimating relationships) and to extend the relationships to small transport aircraft.

ACKNOWLEDGEMENTS

During the course of this study, interviews were conducted with many aircraft manufacturers and suppliers of aircraft components and subassemblies. These interviews constituted a unique and very important part of this study. A large debt of gratitude is owed to these companies and to their employees who provided considerable technical and cost information for aircraft systems and components. Some of them also reviewed the data and analysis presented in this report in those areas with which they were familiar. Since several companies and individuals preferred to remain anonymous, no mention will be made of specific companies and individuals.

EXECUTIVE SUMMARY

This report presents the results of a NASA sponsored study to develop production cost estimating relationships (CERs) and weight estimating relationships (WERs) for commercial and military transport aircraft at the system level. The systems considered in this report correspond to the standard weight groups defined in Military Standard 1374. They are:

Wing	Flight Controls	Auxiliary Power
Tail	Hydraulic	Furnishings and Equipment
Body	Electrical	Instruments
Alighting Gear	Pneumatic	Avionics
Nacelle	Air Conditioning	Load and Handling
Propulsion (less engine)	Anti-Icing	

These systems make up a complete aircraft exclusive of engines. The CER for each system (or CERs in several cases) utilize weight as the key parameter. Weights may be determined from detailed weight statements, if available, or by using the WERs developed in this study which are based on technical and performance characteristics generally available during preliminary design.

The CERs that have been developed provide a very useful tool for making preliminary estimates of the production cost of an aircraft. Likewise, the WERs provide a very useful tool for making preliminary estimates of the weight of aircraft based on conceptual design information. Although the CERs and WERs are based on current technology, any systems which involve new technologies* may be analyzed further using the CER or WER based on current technology as a point of departure. The CERs may also be used to make preliminary estimates of the production cost of modifying an existing

* It is unlikely that a transport aircraft that utilizes new technologies for every system will be designed or produced in the forseeable future. Rather, future transport aircraft will probably be derivatives of current aircraft. Therefore, many of the CERs provided will be appropriate for estimating the costs of future transport designs.

aircraft. For example, if an aircraft requires new wings, the wing CER may be used, as well as CERs for other systems which might be affected such as flight controls and anti-icing. The cost estimate for the new wings based on the CERs would serve only as a point of departure for futher analysis. It should be noted that cost estimates for aircraft involving new technology or modifications cannot be made with acceptable confidence by using existing, aggregate cost models because these models provide no means for making estimates at less than the total airframe level.

Adequate aircraft cost data are not documented at the system level. Therefore, this study used novel data sources for developing system level CERs. Aircraft industry subcontractors with extensive experience in supplying major components and subassemblies were identified and interviewed. The general cost information that they provided on major components and subassemblies was then aggregated by system according to the proportion of total system weight. Since the cost data varied substantially in terms of quality, confidence values were developed for each CER based on an evaluation of its data sources. Thus, anyone using the CERs has a basis for determining which CERs he should be most confident of and which he might want to confirm by using other data.

Three diverse aircraft, a small commercial aircraft (F-28), a wide body commercial aircraft (DC-10) and a military transport (C-141) were selected to test the validity of the CERs. When the estimated total cost was compared to the actual total cost of these aircraft, the estimated costs varied by less than 10 percent. This accuracy is considered very good for cost estimates of a preliminary nature. The WERs developed in this study are based on actual, detailed weight and design data for more than 26 aircraft. To test the validity of the WERs, they were applied to the same aircraft as the CERs (F-28, DC-10-10 and C-141). When the estimated total weights were compared to the actual total weights they varied by less than 6 percent.

The CERs have also been applied using the estimated weights obtained from the WERs. The total costs estimated based on estimated weights have remained within 10 percent of the actual total costs. Thus, the CERs and WERs presented in this report provide unique tools for making relatively quick estimates of the production cost and the weight of commercial and military transport aircraft.

SECTION 1

INTRODUCTION

The purpose of this report is to provide a rapid means for estimating the approximate cost and weight of commercial and military transport aircraft at the system level, exclusive of engines. In this report the system level refers to the seventeen major aircraft systems shown in Figure 1.1.* These systems correspond to the standard weight groups defined in Military Standard 1374. Several of these systems have been further broken down into subsystems for estimating purposes. The cost and weight estimating relationships presented in this report should be useful to NASA, the Defense Department and aircraft manufacturers for estimating the cost of conceptual transport aircraft designs.

The cost estimating relationships developed in this report are based on considerable actual cost data for transport aircraft components and major subassemblies.** Further, the bases for the cost estimating relationships are discussed in detail, which should enable the user to modify them for innovative designs he may be concerned with. This latter feature is of particular interest to NASA so that they can readily estimate the costs of conceptual transport aircraft designs which incorporate technology improvements in individual aircraft systems. Such cost estimates can be used by NASA in screening potential aeronautical research and development programs which it might sponsor.

The significance of the cost estimating relationships presented in this report may be better understood by reviewing the several existing methods for making cost estimates of new aircraft. The method typically used by an aircraft manufacturer is to make detailed industrial engineering estimates of all the components. This method is reasonably accurate, but requires an

---

* The term system is used for a specific functional grouping of components as defined in Section 4 and Appendix C.

**In order not to restrict distribution of this report, proprietary data have been excluded.

Figure 1.1

TRANSPORT AIRCRAFT SYSTEMS*

1. Wing
2. Tail
3. Body
4. Alighting Gear
   - Structure
   - Controls
   - Wheels and Brakes
   - Tires
5. Nacelle
6. Propulsion (Less Engine)
   - Thrust Reverser
   - Engine System
   - Fuel System
7. Flight Controls (Less Autopilot)
8. Hydraulic
9. Electrical
10. Pneumatic
11. Air Conditioning
12. Anti-Icing
13. Auxiliary Power
14. Furnishings and Equipment
15. Instruments
    - Equipment
    - Other
16. Avionics (Including Autopilot)**
    - Equipment
    - Other
17. Load and Handling

Total Airframe

Engines (Bare)

Manufacturer's Empty Weight (MEW)

---

* These systems correspond exactly to the standard weight groups defined in Military Standard 1374, except that the Military Standard combines hydraulics and pneumatics into one standard weight group.

** Avionics are usually not included in "airframe" particularly for military fighters and bombers. However, in this study avionics are considered a part of airframe.

inordinate amount of time and manpower and a data base only a manufacturer would have. For purposes such as conceptual development programs or trade-off studies, such accuracy is not required and such a large expenditure of time and manpower is not warranted.

Two cost models have previously been developed at an aggregate level for the total airframe* to provide approximate costs in a more timely manner. The RAND model, which has gone through several revisions, is widely used.(1,2) This model estimates engineering, tooling, manufacturing labor and material costs for the total airframe as a function of a few aircraft characteristics -- most importantly weight, speed and quantity. A second model which is similar was developed by Planning Research Corporation.(3) While these models are very useful, there are times when a slightly less aggregate, more accurate model which is more responsive to differences in aircraft system design is desirable.

Two such models have been developed - the one contained in this report and one developed by General Dynamics Corporation.(4) The General Dynamics model estimates costs at the major system level based on estimated costs for some study aircraft and some actual aircraft costs.** All types of aircraft are represented in the General Dynamics data base. The applicability of much of that data to transport aircraft is not clear because fighters and bombers are characterized by more costly high performance and low weight components. Furthermore, the reliability and consistency of the data used by General Dynamics in developing the model could not be determined because the data were not documented.

---

* Aircraft less engine and avionics.

** General Dynamics also has a detailed model for airframe structure--wing, tail and fuselage -- which is useful for detailed structural design trade-offs and structural technology assessment. Development of this model was sponsored by NASA and the Air Force.

The model developed in this study, which also estimates costs at the system level, is specifically for transport aircraft and is based on actual cost data. Although cost data were not available at the system level because aircraft manufacturers do not collect or report costs for systems, subcontract and vendor cost data were obtained for major components and subassemblies and these data were the principal basis for developing estimates of system costs.

In Section 2, the aircraft system cost estimating relationships developed in this study are summarized. Then, these estimating relationships are applied to three existing transport aircraft (DC-10-10, C-141A and F-28). The results compare favorably with actual airframe prices. In the remainder of Section 2, the cost methodology, cost data sources and several factors which influence costs are discussed.

The aircraft weight data base and the system weight estimating relationships developed in this study are summarized in Section 3. Weight data were readily available at the group weight or system level. However, substantial effort was required to insure the comparability of the group weight data for aircraft from different manufacturers because the Military Standard 1374 definitions are not very precise as to what items constitute each weight group or system. Further it was necessary to make certain that the weight estimating and cost estimating relationships were consistent, i.e. that what was included in the weight of an aircraft system was the same as what was included in the cost of an aircraft system. The estimating relationships utilize technical and performance characteristics that are generally available during preliminary design as independent variables. These weight estimating relationships show good correlation.

The first three sections of this document summarize the study effort. Detailed derivations and discussions of the cost estimating relationships for each system are contained in Section 4. Detailed derivations and discussions of the weight estimating relationships for each system are contained in Section 5. The appendicies provide supplemental information including discussions of the assumptions made in calculating cumulative average costs from price information, descriptions of recurring cost elements used by aircraft manufacturers and a detailed description of each system.

SECTION 2
SUMMARY OF COST ANALYSIS

Transport aircraft cost data were collected and analyzed, and production cost estimating relationships (CERs) were developed for the seventeen aircraft systems discussed in Section 1. These CERs are summarized below. A demonstration is then given of the application of these CERs to three existing transport aircraft. The cost methodology used in developing the CERs is discussed next. Sources from which cost data were obtained and general factors which influence costs are also discussed. In Section 4, the components which make up each system, relevant technical information and the data and analysis used in developing each CER are discussed in detail.

A. SUMMARY OF COST ESTIMATING RELATIONSHIPS

Parametric CERs have been developed under this study for commercial and military transport aircraft at the system level. These cost estimating relationships are for recurring production costs only and do not include the bare engine cost. They are shown in equation form in Table 2.1. The equations are for cost per aircraft (not cost per pound) and include a quantity scaling factor. These CERs include both the production cost and an assumed aircraft manufacturer's profit of 10 percent.* Each CER is based on a detailed understanding of the major components that make up each aircraft system, the technical and performance characteristics of these components and the costs of these components.

Aircraft system costs were found to correlate reasonably well with system weights as the independent variable. Correlations with other technical and performance characteristics were examined but appeared

* The CERs estimate the aircraft manufacturer's sales price assuming the manufacturer makes a 10 percent profit. This is typical for military aircraft. However, for commercial aircraft, the manufacturer's sales price is typically constant such that the manufacturer loses money until a certain number of units are sold. This is discussed further in Appendix A.

Table 2.1

SUMMARY OF COST ESTIMATING RELATIONSHIPS
(CUMULATIVE AVERAGE COST IN 1975 DOLLARS)

System	Equation	
1. Wing	$C_1 = 1730\ W_1^{0.766}\ Q^{-0.218}$	
2. Tail	$C_2 = 1820\ W_2^{0.766}\ Q^{-0.218}$	
3. Body	$C_3 = 2060\ W_3^{0.766}\ Q^{-0.218}$	
4. Alighting Gear		
A. Structural	$C_{4A} = 1180\ W_{4A}^{0.766}\ Q^{-0.218}$	$(W \leq 10{,}000)$
	$C_{4A} = 136\ W_{4A}\ Q^{-0.218}$	$(W > 10{,}000)$
B. Controls	$C_{4B} = 157\ W_{4B}\ Q^{-0.0896}$	
C. Wheels & Brakes	$C_{4C} = 23.8\ W_{4C}\ Q^{-0.0896}$	
D. Tires	$C_{4D} = 2.0\ W_{4D}$	
5. Nacelle	$C_5 = 3470\ W_5^{0.766}\ Q^{-0.218}$	(w/Acoustic)
	$C_5 = 2660\ W_5^{0.766}\ Q^{-0.218}$	(wo/Acoustic)
6. Propulsion (less engine)		
A. Thrust Reverser	$C_{6A} = 3830\ W_{6A}^{0.766}\ Q^{-0.218}$	(Fan w/Acoustic)
	$C_{6A} = 2800\ W_{6A}^{0.766}\ Q^{-0.218}$	(Fan wo/Acoustic)
	$C_{6A} = 2330\ W_{6A}^{0.766}\ Q^{-0.218}$	(Target wo/Acoustic)
B. ~~Engine~~ Fuel System	$C_{6B} = 61.9\ W_{6B}\ Q^{-0.0896}$	
C. ~~Fuel~~ Engine System	$C_{6C} = 159\ W_{6C}\ Q^{-0.0896}$	
7. Flight Controls	$C_7 = 205\ W_7\ Q^{-0.0896}$	
8. Hydraulic	$C_8 = 54.4\ W_8\ Q^{-0.0896}$	
9. Electrical	$C_9 = 209\ W_9\ Q^{-0.0896}$	$(W \leq 5{,}000)$
	$C_9 = 178\ W_9\ Q^{-0.0896}$	$(W > 5{,}000)$
10. Pneumatic	$C_{10} = 151\ W_{10}\ Q^{-0.0896}$	$(W \leq 400)$
	$C_{10} = 201\ W_{10}\ Q^{-0.0896}$	$(W > 400)$
11. Air Conditioning	$C_{11} = 234\ W_{11}\ Q^{-0.0896}$	

Table 2.1 (Continued)

SUMMARY OF COST ESTIMATING RELATIONSHIPS
(CUMULATIVE AVERAGE COST IN 1975 DOLLARS)

System	Equation
12. Anti-Icing	$C_{12} = 230\ W_{12}\ Q^{-0.0896}$
13. Auxiliary Power	$C_{13} = 243\ W_{13}\ Q^{-0.0896}$
14. Furnishings and Equipment	$\begin{cases} C_{14} = 102\ W_{14}\ Q^{-0.0896} & (W \leq 25{,}000) \\ C_{14} = 115\ W_{14}\ Q^{-0.0896} & (W > 25{,}000) \end{cases}$
15. Instruments	
A. Equipment	$C_{15A} = 1930\ W_{15A}\ Q^{-0.184}$
B. Other	$C_{15B} = 154\ W_{15B}\ Q^{-0.184}$
16. Avionics	
A. Equipment	$C_{16A} = 1930\ W_{16A}\ Q^{-0.184}$
B. Other	$C_{16B} = 154\ W_{16B}\ Q^{-0.184}$
17. Load and Handling	$C_{17} = \frac{W_{17}}{W_3} C_3$
18. Final Assembly and Delivery	$C_{18} = \sum_{1}^{17} C_i \times 0.25$

Where: C = Cumulative average cost for Q units in constant 1975 dollars including an assumed 10 percent profit.

W = Weight of system or subsystem

Q = Production quantity

Subscripts refer to the numbers in the left hand column. For example, W_1 = wing weight.

to offer no advantages over weight.* At later stages of design other independent variables such as parts count and commonality might be included to improve estimates. However, such data are generally not available during preliminary design when use of this model is intended.

The equations in Table 2.1 were developed for design technologies and manufacturing processes which are currently in use. They may not, for example, accurately represent new technologies where weight is significantly reduced while unit cost changes little. Therefore, if the user is interested in assessing new technologies or manufacturing processes he is advised to carefully consider the data upon which the equations are based as discussed in Section 4.

It is demonstrated in Section 2B that the CERs in Table 2.1 provide reasonably accurate estimates of the total cost of existing transport aircraft. However, it is possible that compensating errors exist within this set of equations and the user is, therefore, advised to consider the data upon which they are based if his purpose is to estimate the cost of only a few aircraft systems rather than the cost of a complete aircraft.

Transport aircraft systems are ranked by percent of total cost in Table 2.2. These percentages are very approximate and may vary significantly for specific designs. They do, however, provide an indication as to the relative magnitude of the cost of the various systems.

B. APPLICATION OF THE COST ESTIMATING RELATIONSHIPS

Cost estimates have been made for the DC-10-10, C-141A and F-28 using

* The aggregate cost models developed by RAND and Planning Research Corporation indicate that speed is a significant independent variable for estimating aircraft costs. However, these cost models included all types of aircraft. For current transport aircraft speed differs only slightly (about $\pm$ 10 percent) and, therefore, speed was not a significant characteristic in this study. If a future generation of transport aircraft is pushed to the limit of subsonic performance then speed should be reconsidered.

Table 2.2

AIRCRAFT SYSTEM RANK BY
APPROXIMATE PERCENT OF TOTAL COST*

Rank	System	Percent of Total Aircraft Cost
1	Body	20
2	Wing	18
3	Furnishings and Equipment (commercial)	10
3	Avionics	10
5	Nacelle	7
6	Propulsion	6
7	Tail	5
7	Alighting Gear	5
7	Flight Controls	5
10	Electrical	4
10	Instruments	4
12	Air Conditioning	2
13	Auxiliary Power	1
13	Pneumatic	1
13	Anti Icing	1
13	Hydraulic	1
17	Load and Handling	<1

* Percentages are approximately the same for both commercial and military aircraft except furnishings and equipment which accounts for only about 3 percent of the cost of military aircraft.

the equations in Table 2.1. The results are presented in Tables 2.3, 2.4 and 2.5, respectively. The weights used are their actual weights as provided in Sections 3 and 5. A production quantity of 100 was assumed. The estimated total cost for the aircraft is compared in Tables 2.3, 2.4, and 2.5 to their "actual cost." The actual cost of the C-141A including profit was available from government data. The actual cost of the two commercial aircraft including an assumed 10 percent profit was estimated from sales price data based on assumed non-recurring costs and breakeven quantities.* When the estimated costs were compared with the actual costs it was found that the cost of the DC-10-10 was underestimated by 4 percent while the costs of the C-141A and F-28 were overestimated by 10 and 4 percent, respectively. A range of -4 to +10 percent is quite acceptable for the purpose for which these cost estimating relationships are intended, i.e. to provide rapid estimates of the approximate cost of conceptual designs. The significance of these relatively small errors is indicated by the fact that the three aircraft for which the cost estimating relationships were demonstrated represent a broad spectrum of current transport aircraft as:

- Two were produced by different U.S. manufacturers (DC-10-10 by the Douglas Aircraft Company and C-141A by the Lockheed-Georgia Company) and one by a foreign company (F-28 by Royal Netherlands Aircraft Factories Fokker in the Netherlands).
- Two are commercial (DC-10-10 and F-28) and one is military (C-141A).
- The two commercial aircraft are of very different size (DC-10-10 manufacturer's empty weight (MEW) is 203,760 pounds compared to 29,178 pounds for the F-28). The military aircraft is medium sized (C-141A MEW is 110,233 pounds).
- The aircraft represent different states-of-the-art.**

* These assumptions are discussed in detail in Appendix A.

**Although the C-141A and the F-28 were designed at about the same time, it seems reasonable to assume that a military aircraft would use more advanced technologies than a commercial aircraft.

Table 2.3

DC-10-10 COST ESTIMATE*
(CAC_{100} IN 1975 $)

System	Weight	Cost per pound	Cost ($000)	Percent of Total Cost (Less Final Assembly and Delivery)
Wing	48,990	$ 51	$ 2,481	15.3
Tail	13,657	72	981	6.1
Body	44,790	62	2,759	17.0
Alighting Gear	(18,820)	(40)	(755)	(4.7)
Structure	10,672	50	532	3.3
Controls	1,424	104	148	0.9
Wheels and Brakes	4,456	16	70	0.4
Tires	2,267	2	5	<0.1
Nacelle **	8,493	153	1,300	8.0
Propulsion (less engine)**	(7,673)	(148)	(1,134)	(7.0)
Thrust Reverser (fan)	5,382	188	1,012	6.3
Engine System	441	104	46	0.3
Fuel System	1,850	41	76	0.5
Flight Controls	5,120	136	695	4.3
Hydraulic	2,363	36	85	0.5
Electrical	5,366	118	632	3.9
Pneumatic	1,787	133	238	1.5
Air Conditioning	2,386	155	370	2.3
Anti-Icing	416	151	63	0.4
Auxiliary Power	1,589	161	256	1.6
Furnishings and Equip.	38,072	68	2,570	15.9
Instruments	1,349	447	602	3.7
Avionics	2,827	447	1,262	7.8
Load and Handling	62	60	4	<0.1
Sub-Total	203,760	78	16,187	100.0
Final Assembly	--	--	4,047	--
Total (less bare engines)	203,760***	$ 98	$ 20,234	--

$$\frac{\text{Estimated } CAC_{100}}{\text{Actual}^{+}\ CAC_{100}} = \frac{\$20,234}{\$21,100} = 0.96$$

* $\overline{CAC_{100}}$ = cumulative average cost for 100 aircraft including assumed 10 percent profit.

** With acoustic treatment.

***Manufacturer's Empty Weight (less bare engines).

+ Estimate based on assumptions discussed in Appendix A.

Table 2.4

C-141A COST ESTIMATE*
(CAC_{100} IN 1975 $)

System	Weight	Cost per Pound	Cost ($000)	Percent of Total Cost (Less Final Assembly and Delivery)
Wing	34,262	$ 55	1,887	20.0
Tail	5,745	87	505	5.3
Body	28,578	68	1,955	20.7
Alighting Gear	(10,529)	(45)	(473)	(5.0)
Structure	5,287	58	308	3.3
Controls	1,161	104	121	1.3
Wheels & Brakes	2,575	16	41	0.4
Tires	1,506	2	3	<0.1
Nacelle	5,630	129	727	7.7
Propulsion (less engine)	(5,780)	(101)	(583)	(6.2)
Thrust Reverser (target)**	3,200	129	413	4.4
Engine System	1,014	105	106	1.1
Fuel System	1,566	41	64	0.7
Flight Controls	3,448	136	468	5.0
Hydraulic	1,504	36	54	0.6
Electrical	3,015	138	417	4.4
Pneumatic	659	133	88	0.9
Air Conditioning	1,547	155	240	2.5
Anti-Icing	598	152	91	1.0
Auxiliary Power	635	161	102	1.1
Furnishings and Equip.	4,362	68	295	3.1
Instruments	899	388	348	3.7
Avionics	2,938	411	1,207	12.8
Load and Handling	104	70	7	<0.1
Sub-Total	110,233	86	9,447	100.0
Final Assembly	--	--	2,362	--
Total (less bare engines)	110,233***	$ 101	$11,809	--

$$\frac{\text{Estimated } CAC_{100}}{\text{Actual } CAC_{100}} = \frac{\$11,809}{\$10,720} = 1.10$$

* CAC_{100} = cumulative average cost for 100 aircraft.

** Without acoustic treatment.

***Manufacturer's Empty Weight (less bare engines).

Table 2.5

F-28 COST ESTIMATE*
(CAC_{100} IN 1975 $)

System	Weight	Cost per Pound	Cost ($000)	Percent of Total Cost (Less Final Assembly and Delivery)
Wing	7,526	$ 79	$ 591	18.4
Tail	1,477	121	179	5.6
Body	6,909	95	659	20.5
Alighting Gear	(2,564)	(59)	(146)	(4.5)
Structure	1,461	79	115	3.6
Controls	205	104	21	0.7
Wheels and Brakes	590	16	9	0.3
Tires	308	2	1	<0.1
Nacelle**	866	200	173	5.4
Propulsion (less engine)	(988)	(163)	(144)	(4.5)
Thrust Reverser (target)**	693	185	128	4.0
Engine System	57	105	6	0.2
Fuel System	238	42	10	0.3
Flight Controls	1,404	136	191	5.9
Hydraulic	346	35	12	0.4
Electrical	953	139	132	4.1
Pneumatic	60	133	8	0.2
Air Conditioning	520	155	81	2.5
Anti-Icing	520	152	79	2.5
Auxiliary Power	320	159	51	1.6
Furnishings and Equip.	3,535	68	239	7.4
Instruments	267	446	119	3.7
Avionics	923	446	412	12.8
Load and Handling	0	0	0	0.0
Sub-Total	29,178	121	3,216	100.0
Final Assembly	--	--	804	--
Total (less bare engines)	29,178***	$149	$ 4,020	--

$$\frac{\text{Estimated } CAC_{100}}{\text{Actual}^{+} \ CAC_{100}} = \frac{\$\ 4,020}{\$\ 3,870} = 1.04$$

* CAC_{100} = cumulative average cost for 100 aircraft including assumed 10 percent profit.

** Without acoustic treatment.

***Manufacturer's Empty Weight (less bare engines).

\+ Estimate based on assumptions discussed in Appendix A.

C. SUMMARY OF COST METHODOLOGY

The first and most difficult step in developing aircraft system CERs was the collection of meaningful cost data. Cost data were not available at the system level because aircraft manufacturers do not collect or report costs by system. However, subcontract and vendor* cost data were available for many major components and subassemblies. More specifically, the cost data for the wing, tail, body, alighting gear, nacelle and propulsion systems were based largely, but not entirely, on subcontractor data from government contract information for military transports. Cost data for the other systems were based largely, but not entirely, on cost information of an approximate, generic nature obtained directly from subcontractors. The cost data were normalized for inflation and build quantity, as required. The available cost data were then carefully analyzed together with technical and performance data and cost estimates were derived for the various components and subassemblies. System level cost estimates were developed by aggregating cost estimates for the major components and subassemblies based on the relative weights of the components and subassemblies in accordance with the following equation:

$$C_s/W_s = \sum_i \frac{W_i}{W_s} \quad (C_i/W_i)$$

Where: C = cost

W = weight

s = system

i = each major component or subassembly

For example:

Major Component or Subassembly	Component Percent of Total System Weight	Cost Per Pound
A	25%	$ 50
B	65	150
C	10	25
Total System	100%	$ 113

* No differentiation is made in this report between subcontractors and vendors. For convenience, the term subcontractor will be used to refer to both.

In a few cases, relevant cost data were not obtainable. therefore, assumptions had to be made regarding some major components and subassemblies. These assumptions and the sensitivity of the cost estimates to them are discussed in Section 4.

When the component percent of total system weight varied significantly by size or type of aircraft and sufficient data were available, then separate cost estimates were determined for each of four classes of aircraft. These classes are the following: small commercial (fewer than 100 passengers, e.g., BAC-111, F-28, DC-9-10); medium sized commercial (100 to 200 passengers, e.g., 727-100, 990, 707-320, DC-8-62); wide body commercial (200 to 400 passengers, e.g., 747, DC-10-30, L-1011); and military transport (e.g., KC-135, C-141, C-130, C-5). The aircraft indicated for each class are examples only. Data related to only one "generic" type aircraft, either the DC-9-10 or the DC-9-30. for example, were used because it was felt that using both might bias the results of the weight breakdowns toward a particular design philosophy or technology.

The system cost estimates discussed above represent only a portion of an aircraft manufacturer's recurring production costs. This may best be understood by referring to the typical breakout of recurring transport aircraft costs shown in Table 2.6.[14] In-house production and subcontractor costs amount to about 66 percent of the total recurring production cost of a transport aircraft. The remaining costs are called "In-house Assembly" and are the cost of integrating the various major components and subassemblies into a complete aircraft ready to be delivered. The system cost estimates, which are based on subcontractor data, are used to estimate all of the in-house production and subcontractor (i.e., outside production and purchased equipment) costs. This is considered valid since nearly every major component or subassembly on a transport aircraft has been made by a company other than the aircraft manufacturer. Thus, although an aircraft is composed of parts produced by the aircraft manufacturer and by subcontractors, it could conceivably consist only of parts produced by subcontractors and assembled by the manufacturer. In any case, the assumption is made that the aircraft manufacturer's "make or buy decision" is based primarily on

Table 2.6

RECURRING PRODUCTION COST ELEMENTS
FOR TRANSPORT AIRCRAFT

Cost Element*	Percentage of Total Cost**
In-House Production	(32) %
Fabrication	11
Sustaining Engineering	8
Sustaining Tooling	5
Raw Material	8
Subcontractor	(34)
Outside Production	22
Purchased Equipment	12
In-House Assembly	(34)
Quality Control	5
Minor Assembly	7
Major Assembly	(22)
Sectional Assembly	7
Installation & Checkout	9
Miscellaneous	6
Total	100%

* See Appendix B for cost element descriptions. The cost elements include direct and indirect costs. Direct costs are those that can be identified with a particular output objective such as a specific aircraft. Indirect costs are those which are incurred for common or joint objectives and must, therefore, be shared in some equitable manner. Indirect costs are often synonymous with overhead and general and administrative (G&A) costs. For a thorough discussion of indirect costs see: Martinson, Major Otto B., A Standard Classification System for the Indirect Costs of Defense Contractors in the Aircraft Industry, U.S. Government Printing Office, 1969.

**Adjusted to cumulative average cost for 100 aircraft.

lowest cost.* Therefore, the subcontractor costs should closely approximate the aircraft manufacturer costs for producing a similar item. It should be noted that in Section 4, in-house production and subcontractor costs are not differentiated and are referred to simply as subcontractor costs.

In order to arrive at the total recurring aircraft cost, in-house assembly costs must be added to the system cost estimates discussed above. Based on Table 2.6, system cost estimates for in-house production and subcontractor costs must be multiplied by a factor of 1.52 (i.e., 1/0.66) to arrive at an approximation of the total cost of a transport aircraft including in-house assembly but exclusive of any profit for the aircraft manufacturer. However, in developing CERs for the individual aircraft systems it was decided to separate the in-house assembly costs into (1) those related to integrating the various major components and subassemblies into a complete system and (2) those related to final assembly of the systems into a complete aircraft. Although an aircraft is not constructed by producing complete, individual systems and then integrating them, but rather by a series of operations where systems in a particular section of an aircraft are built up simultaneously with other systems, the distinction between "system-level assembly" and "final assembly" was considered useful in showing a hypothetical, complete system cost. While no precise data were available to separate these assembly costs, it was assumed that system-level assembly would include all minor assembly, half of installation and checkout and half of quality control. From Table 2.6, these items account for about 14 percent of recurring production costs. Therefore, in-house production and subcontractor costs must be multiplied by a factor of 1.21 (i.e., 0.80/0.66) to account for system-level assembly.

* It is recognized that factors other than lowest cost are occasionally significant. For example, lenders may require that subcontractors be used in order to spread the risk and foreign subcontractors are occasionally used to stimulate foreign sales. However, even in such cases it is not expected that the subcontractor's cost would differ significantly from the manufacturer's cost.

If a nominal 10 percent profit is assumed and allocated to the individual systems,* then in-house production and subcontractor costs must be multiplied by a factor of 1.33** (i.e., 1.21 x 1.10) to arrive at system-level CERs. Final assembly costs which are the remaining portion of in-house assembly costs are about 20 percent of recurring production costs. Therefore, final assembly is 25 percent (i.e., 0.20/0.80) of the sum of all system level CERs. This factor for final assembly is substantiated by another study[16] which indicates a factor of 13 to 25 percent of total recurring production costs.

Because the quality of the data available for this study ranged from excellent to poor, the confidence the authors have in the various cost estimating relationships they have developed is an important issue. Attributing confidence values to cost estimating relationships is necessarily a subjective task. The categories and related confidence values presented in Table 2.7 were developed by the authors to help reduce arbitrariness. Confidence values represent an important, innovative aspect of this study as they provide a numerical (albeit subjective) representation of the confidence the authors have in the data upon which the cost estimating relationships are based. They should, therefore, be useful in indicating areas where potential errors might occur in applying the CERs or where further study could be done.

---

* The assumption of a 10 percent profit is discussed in the footnote on page 2-4. Profit was allocated to the individual systems in order to reasonably attribute as much of the cost as possible to them. The total estimated cost of an aircraft is the same whether profit is broken out by system or lumped as a final add on.

**This factor may vary significantly for the different systems. For example , system assembly costs are expected to be greater for an electrical system (given the labor required for wiring) than for an auxiliary power plant (which is relatively simple to install). However, since no valid basis was determined for allocating these costs proportionately by system, they were treated as a fixed percentage of in-house production and subcontractor costs. The cost data used for the tail and nacelle included assembly of components into the total system since the subcontractors for these systems provided essentially the complete system. Therefore, and approximate factor of 1.21 was used for the tail and nacelle.

Table 2.7

BASIS FOR ATTRIBUTING CONFIDENCE VALUES TO COST ESTIMATING RELATIONSHIPS

Source of Data	Confidence in CER Reliability and Validity
Extensive detailed costs available and accuracy confirmed by industry expert(s)	9.5-10
Estimate provided by industry expert(s) and verified by some actual data	9 - 9.5
Similar estimate provided by at least two industry experts or reported actual costs	8 - 9
Estimate provided by one industry expert only	6 - 8
Estimate based on one reported actual cost	5 - 7
Estimate based on judgment using data for similar item as basis for extrapolation	3 - 6
Other assumption	0 - 3

Table 2.8 lists the confidence values assigned to each of the cost estimating relationships summarized in Table 2.1. Confidence values were determined at these levels by prorating values assigned to major components and subassemblies in accordance with the following equation:

$$V_s = \sum_i \frac{C_i}{C_s} V_i$$

Where: V = confidence value

C = cost

s = system

i = each major component or subassembly

It is stressed that these confidence values are ordinal numbers and are used to reflect only the relative confidence attributed to the various cost estimating relationships ranging from high (10) to low (0). In other words, a cost estimating relationship for which a 7.0 confidence value has been attributed is based on data that is assumed to be more reliable than one with a 6.0 rating and less reliable than one with an 8.0 rating.

D. SOURCES OF COST DATA

It is necessary to obtain valid cost data at some desired level of detail in order to develop reliable cost estimating relationships such as those summarized above. Obtaining such costs was a problem for this study and it was necessary to investigate many potential sources of data. Each general data source is discussed briefly below to indicate some advantages, problems and disadvantages associated with it.

Aircraft Manufacturers

Aircraft manufacturers would appear to be the most likely and most complete source of cost data for transport aircraft systems. This source proved to be of little value. Whereas weight and volume data are readily available at the aircraft weight group or system level, cost data do not appear to be documented by aircraft manufacturers at the system level except in some cases for structural systems (wing, tail and body). Aircraft costs have been traditionally broken out into categories such as engineering,

Table 2.8

SUMMARY OF CONFIDENCE VALUES FOR COST ESTIMATING RELATIONSHIPS

System	Confidence Value
Wing	8.0
Tail	9.0
Body	7.0
Alighting Gear	
Structure	8.0
Controls	5.0
Wheels & Brakes	8.0
Tires	9.5
Nacelle	6.0
Propulsion (less engine)	
Thrust Reverser	6.0
Engine System	5.5
Fuel System	4.1
Flight Controls	6.9
Hydraulic	6.3
Electrical	7.9-8.3
Pneumatic	4.9-5.8
Air Conditioning	7.8
Anti-Icing	4.0
Auxiliary Power	7.9-8.4
Furnishings & Equipment	5.0-7.3
Instruments	8.0
Avionics	8.0
Load & Handling	3.0
Subtotal*	7.2
Final Assembly and Delivery	7.5
Total (less bare engines)*	7.3

* The subtotal and the total confidence values shown are weighted averages based on the estimated percentage of the total cost for each of the aircraft systems. The estimated costs for the DC-10-10, C-141A, and F-28 produced identical weighted averages for the subtotal and total.

tooling, manufacturing, labor and material, but within these categories they have not been associated with systems.

The problem in obtaining system cost information is illustrated by the results of a Lockheed study[5] pertaining to C-5 cost, schedule and technical characteristics performed for the NASA Johnson Space Center. In this study, Lockheed was to provide C-5 costs by system (these systems are similar but not necessarily identical to those defined in this study). Lockheed made use of detailed accounting system records which were on computer tape. Even with such detailed information, which was readily amenable to computer manipulation, only a portion of the cost of each system could be identified. This included major subcontract effort and some of the prime-contractor design engineering effort. The cost related to in-plant manufacturing and assembly effort performed by Lockheed could not be identified sufficiently to be allocated to specific systems.

The biggest problem with obtaining cost data from aircraft manufacturers, however, was their reluctance to provide specific cost information at any level of detail. Aircraft manufacturers guard their cost data related to aircraft manufacturing, pricing or profit very carefully. Even though Science Applications, Inc. routinely handles proprietary data, manufacturers would not provide specific cost information because of intense competition for the sale of transport aircraft.

Government Cost Information

The cost estimating relationships developed in the previous report[6] were derived primarily from data obtained from government sources. The specific sources of these data, which were listed in detail in that report, consisted mostly of data on major subcontracted items and on vendor supplied equipment and avionics which were found in contract records, proposals and reports furnished to the government by the manufacturers of such military transport aircraft as the: C-130, KC-135, C-141, and C-5A.

While these data were used in developing cost estimating relationships, they were incomplete and additional data were required from other sources. Some of the limitations and problems with government cost information are:

- Government contract cost data are not sufficiently detailed for all systems.
- Government contract cost data are available only for the few military transport aircraft. While most of the systems have only minor functional differences between military and commercial transport aircraft, there are cases when they have little in common. Furnishings is one of the more obvious examples.
- The C-5A is the newest military transport aircraft for which any cost data were available and it reflects technology which is over ten years old. Further, many C-5A data are of questionable value because of innumerable, extraordinary problems related to the unique contract under which it was procured and expensive methods employed to keep weight below the design threshold.
- Contract cost information typically summarizes costs for many production units. Using this to determine an average unit cost (even one adjusted to reflect an assumed learning curve) ignores the fact that the aircraft manufacturing process is a dynamic one where the tasks assigned to a subcontractor occasionally vary greatly over the life of the contract. For example, the subcontract under which a nacelle is manufactured might initially require that only the shell be provided; by the time the subcontract is terminated it may have been modified several times until, finally, a complete power plant build-up is provided.

Spare Parts Cost Data

Alternative sources of cost data were sought to expand the data base and to improve confidence in the cost estimating relationships which were developed in the previous study. A substantial effort was spent investigating spare parts cost data as a possible alternative.

It was recognized at the outset that spare parts probably have a significantly higher profit margin than identical parts manufactured for immediate assembly line use. However, it was felt that if spares prices were uniformly higher, they might be adjusted so as to provide useful, supplemental cost information. The problem was to obtain prices for spare parts that could be related to weight or other characteristics so that cost estimating relationships could be developed. Government, rather than commercial spare parts prices were investigated because they were more easily attainable.

Government spare parts price data were obtained for spare assemblies and components. These data were determined to be of limited value for the following reasons:

- Spare parts are only those parts that are stocked because they are typically replaced in the course of normal maintenance. Parts that are replaced only rarely are obtained from the manufacturer on an as needed basis. Thus, spare parts represent only limited portions of a system.
- Spare parts prices represent the amount of the last unit purchased. This results in several severe problems which make the data of little use. These include: the fact that the price specified is often a function of the quantity bought per order (set-up time is amortized over quantity and when a small quantity is produced, the unit price is greatly increased); where the item would fall in relation to the total quantity produced and the effect of a learning curve is unknown because the aggregate production quantity is unknown; and the effect of inflation cannot be determined because the date of purchase is not indicated.
- Spares parts prices are typically available only for components below the subassembly level. This leads to the problem of determing whether and how assembly costs would affect the price of a complete unit.

- It is difficult to associate price information with parts numbers.
- Weights of spare parts frequently could not be obtained so that cost per pound estimating relationships could not be determined.

Major Aircraft Industry Subcontractors

Nearly every major item on an airplane has, at one time or another, been manufactured by a company other than the aircraft manufacturer. Thus, major aircraft industry subcontractors represented a huge potential source of cost data, and because of this attempts were made to contact those with significant experience in the production of major system components and subassemblies. In fact, whenever possible, more than one manufacturer of a particular item was contacted to eliminate or reduce possible individual biases.

Initially it was thought that, like the aircraft manufacturers, subcontractors would be reluctant to discuss the price of their products. Although experience verified that, with few exceptions, subcontractors would not provide detailed selling prices for specific items, most were willing to discuss price in general terms as they recognized that such prices would not differ markedly from those charged by their competition. This cooperation significantly increased our knowledge regarding the prices and factors influencing the prices of major system components.

The following points characterize data furnished by the subcontractors:

- Prices were provided for both commercial and military transport aircraft systems and, when appropriate, explanations were provided as to why they differed.
- Prices were provided in 1975 dollars and, thereby, eliminated the application of potentially erroneous inflation assumptions. (Inflation is discussed briefly in Section 2E.)
- Explanations were provided as to how price would normally be expected to vary if changes in design, performance or reliability were specified or if a new technology was applied.

- Examples were also provided regarding other conditions that might influence prices. These include quantities purchased under a particular contract, inflation, the need to be competitive to win a particular procurement and the relationship they have experienced in former dealings with customers.

While most of the information provided by major subcontractors did not consist of actual prices for specific items, the approximate price information that was provided was considered to be representative and accurate enough for the purposes of this study. Furthermore, the explanations provided were very useful in relating the costs of major components and subassemblies to total system costs. Thus, using this subcontractor information to complement and supplement that obtained from other sources enabled cost estimating relationships to be developed that were based on a detailed understanding of the aircraft systems.

E. FACTORS WHICH INFLUENCE COST

Some of the factors which influence cost are discussed below. While the following comments will not apply in all cases, they should be considered before using cost estimating relationships to predict the cost of an airframe or aircraft system so that potential pitfalls may be avoided.

The Relationship Between Weight and Cost

The cost estimating relationships summarized earlier estimate cost as a function of weight at the system level. It must be stressed, however, that such cost estimating relationships hold only for a specified state-of-the-art or class of service. Should a dramatic technological breakthrough rather than evolutionary design advancement occur or should a weight reduction program be implemented, it is likely that these relationships would be invalidated. If, for example, efforts are undertaken to dramatically reduce weight for a given item, its cost per pound would typically increase significantly.

The following was written about the cost/weight relationship pertaining to aircraft hydraulic actuators. It is felt, however, that it is generally applicable throughout much of the aircraft industry.

"Although a favorite game of estimators is to establish a price per pound on aircraft machinery, it is obviously a fact that a very lightweight design will be more expensive than an ordinary design. A lightweight design requires more careful stress analysis, additional machining, exotic materials, and design concentration on an additional factor beyond performance and reliability.

"Weight reduction incentives may be in several forms; a generalized desire on the part of the customer to reduce weight is usually inadequate. A very heavy design probably will not be chosen in the first place but an ordinary design will be chosen if there is no serious weight competition.

"Supplier experience has a strong influence on weight. As weight is emphasized from time to time, the designer learns what designs are reliable and yet lightweight. He also learns intuitively what factors affect the weight and how the weight can be reduced economically. Here in depth experience in a given field is of considerable value and will contribute much to the reduction of weight.

"The procuring agency or customer can have a very serious affect on the weight of an article. Cost being a primary penalty for lightweight design, if procurement is based only on price, then a negative incentive exists for low weight. If on the other hand a weight is stipulated as a primary factor and there is a stated dollars per pound incentive the supplier can evaluate the relative merits of a lighter weight configuration. ...without a specific designated dollars per pound advantage specified by the procuring agency, all suppliers are essentially in the dark as to how far they should go in their weight reduction studies."(7)

Inflation and Learning

Two factors frequently cited as influencing cost are: inflation and "learning." Inflation is simply an increase in the volume of money relative to available goods which results in a substantial rise in the general price level. Under inflation then, an item will cost more to produce tomorrow than it does today using the same mix of materials, capital and labor.

For many years the industry has made use of what variously have been called "learning," "progress," "improvement," or "experience" curves to predict reductions in cost as the number of items produced increases. The learning process is a phenomenon that prevails in many industries; its existence has been verified by empirical data and controlled tests. Although there are several hypotheses on the exact manner in which the learning or cost reduction occurs, the basis of learning-curve theory is that each time the total quantity of items produced doubles, the cost per item is reduced to some constant percentage of the previous cost. Alternative forms of the theory refer to the incremental (unit) cost of producing an item at a given quantity or to the average cost of producing all items up to a given quantity. For example, if the cost of producing the 200th unit of an item is 80 percent of the cost of producing the 100th item, and if the cost of the 400th unit is 80 percent of the cost of the 200th, and so forth, the production process is said to follow an 80 percent unit learning curve. If the average cost of producing all 200 units is 80 percent of the average cost of producing the first 100 units, the process follows an 80 percent cumulative average learning curve. Either formulation of the theory results in a power function that is linear on logorithmic grids.(8)

Although reference is frequently made to a learning curve of some specified percent for an aircraft, it must be recognized that this is a composite of many different learning curves. For example, fabrication labor, minor assembly labor, major assembly labor, material and subcontractor or vendor supplied items may all have different learning curves.

Thus, inflation acts to increase cost while learning acts to reduce it. Even though these factors function independently of one another, their combined effect should frequently be considered by the analyst attempting to make extrapolations from reported cost data because one may tend to offset the impact of the other.

Military Versus Commercial Aircraft

Because military and commercial transport aircraft are occasionally different models of the same basic aircraft, it would be expected that the cost and construction of common systems would be identical. While this is frequently the case, notable exceptions exist. These exceptions are caused by both the uses to which the aircraft are put and the contractual process under which they are produced. Some examples of differences between military and commercial aircraft are discussed below and in Section 4. These differences do not appear to be large enough to invalidate the cost estimating relationships that have been developed when they are applied to determine the cost of a complete aircraft. However, the data upon which the relationships were based should be reviewed and appropriate adjustments should be considered when only the cost of a particular system is sought.

One cause for differences between military and commercial transport aircraft components is the manner in which they are used. While a typical Air Force cargo aircraft flies less than 500 hours annually, a commercial transport may approach 3,600 annual flying hours. Air Force flying hours are, however, more demanding on the equipment which, in part, results in the lower expected life of some military aircraft components.

Other differences in cost between military and commercial aircraft are caused by differing contractual requirements among the agencies overseeing production. For example, some military components must be hardened against nuclear attack and the FAA has very strict fire and smoke regulations. Each of these requirements increases the cost of the aircraft upon which it is implemented. As another example, required use of high reliability (Hi-Rel) parts for military electrical components may cause them to cost two to ten times their commercial equivalents.

<u>Other Factors</u>

The extent to which existing technology will meet the requirements of a particular system on a new aircraft and the degree to which off-the-shelf components can be used in manufacturing will greatly influence cost. A change in technology may either increase or decrease the cost depending on the specific case. Technological advances are often incorporated after production has started. This usually increases the cost and perturbs the learning curve.

Another factor that influences cost is the difference in design philosophies among the aircraft manufacturers. Each often has its own idea regarding how a requirement is best fulfilled. Their approach to and need for additional outside manufacturing capability also influences cost. For example, Boeing and Douglas generally design their own systems and then procure components from several subcontractors while Lockheed often has a single subcontractor design and produce a complete system.

SECTION 3

SUMMARY OF WEIGHT ANALYSIS

Weight and technical data were collected and analyzed for 26 commercial and military transport aircraft.* Using these data, weight estimating relationships (WERs) were developed for the 17 aircraft systems discussed in Section 1.** These WERs are summarized below. Th is followed by a summary of the weight and technical data for the 26 transport aircraft. A demonstration is then given of these WERs for three existing transport aircraft. In Section 5, detailed weight and technical data are presented and analyzed and the derivation of each WER is discussed.

A. SUMMARY OF WEIGHT ESTIMATING RELATIONSHIPS

WERs have been developed under this study for commercial and military transports at the system level. These WERs, which sum to the "manufacturers empty weight" less the bare engine weight, are shown in Table 3.1. The symbols used in the equations are defined in Table 3.2. Only those design characteristics which are likely to be known during the conceptual phase of the aircraft development were used. Any design and technology features, which were not common to the majority of the vehicles in the data base nor used under normal conditions, were removed before correlations were made. Then, where appropriate, separate adjustments for special features were calculated.

In some cases, separate WERs were developed for major components of a system in order to have a WER that corresponded with each of the CERs discussed in Sections 2 and 4. Also, for some systems, component WERs were developed to improve correlations (e.g., the nacelle system is broken into

* For some aircraft systems, additional data were available and were used.

**The systems for which WERs were developed correspond exactly to the standard weight groups defined in Military Standard 1374, except the Military Standard combines hydraulics and pneumatics into one standard weight group and includes the autopilot with flight controls. Not to have put the autopilot with avionics would have required arbitrarily splitting the integrated flight guidance and control system weight for newer aircraft between flight controls and avionics whereas the autopilot weight for older aircraft was readily available.

Table 3.1

SUMMARY OF WEIGHT ESTIMATING RELATIONSHIPS

1. Wing

$$W_1 = 0.930\ I_w + 6.44\ S_w + 390$$ Medium and Large

$$W_1 = 4.24\ I_w + 0.57\ S_w$$ Small

where: $$I_w = \frac{U\ (AR)^{1.5}\ (ZFW/TOGW)^{0.5}(1+2\ \lambda\ )(W/S)S_w^{1.5}10^{-6}}{t/c\ (\cos\ \Omega c/4)(1 + \lambda\ )}$$

Alternative Wing Equation

$$W_1 = 0.112\ TOGW - 1{,}720$$

2. Tail

$$W_2 = 5.03\ S_t$$ Conventional Tail

$$W_2 = 6.39\ S_t$$ "T" Tail

3. Body

$$W_3 = 161\ N_p - 5{,}110$$ Medium and Large Commercial

$$W_3 = 110\ N_p$$ Small Commercial

$$W_3 = 0.467\ S_b^{1.277}$$ Military

4. Alighting Gear

$$W_4 = \sum_{i=A}^{D} W_{4i} + \sum_{i=E}^{H} W_{4i}$$

4.' Basic Alighting Gear

$$W_4' = \sum_{i=A}^{D} W_{4i} = W_{4A} + W_{4B} + W_{4C} + W_{4D}$$

Table 3.1 (Continued)

SUMMARY OF WEIGHT ESTIMATING RELATIONSHIPS

4.' Basic Alighting Gear (Continued)

$W_4' = 0.0440\ (TOGW) - 672$	Medium and Large Commercial
$W_4' = 0.0439\ (TOGW) - 2{,}050$	Medium and Large Military
$W_4' = 0.0395\ (TOGW)$	Small Commercial
$W_4' = 0.0302\ (TOGW)$	Small Military

4A. Alighting Gear Structure

$$W_{4A} = W_4'\ [0.450 + 23.1 \times 10^{-8}\ (TOGW)]$$

4B. Alighting Gear Controls

$$W_{4B} = W_4'\ [0.130 - 6.56 \times 10^{-8}\ (TOGW)]$$

4C. Wheels and Brakes

$$W_{4C} = W_4'\ [0.268 - 8.12 \times 10^{-8}\ (TOGW)]$$

4D. Tires

$$W_{4D} = W_4'\ [0.152 - 8.38 \times 10^{-8}\ (TOGW)]$$

4E. Add for Low Pressure Tires

$$W_{4E} = W_4'\ [0.125 - 0.0102 \times 10^{-5}\ (TOGW)]$$

4F. Add for each ft./sec. Increase in Sink Speed

$$W_{4F} = 0.038\ W_4'$$

4G. Add for Prepositioning and Inflate/Deflate Requirements

$$W_{4G} = 0.184\ W_4'$$

Table 3.1 (Continued)

SUMMARY OF WEIGHT ESTIMATING RELATIONSHIPS

4H. Subtract for Carbon Brakes

$$W_{4H} = W_4' \, [0.0786 - 0.071 \times 10^{-6} \, (TOGW)]$$

5. Nacelle

$$W_5 = W_{5A} + W_{5B} + W_{5C}$$

5A. Cowl

$$W_{5A} = 0.0415 \, N_e I_c$$

$$\text{where } I_c = (1.316 + 0.0125 \, D_f) \, L_i D_f + L_f \, D_f + (1.316 + 0.0191 \, D_f) \, L_{fex} \, D_f + L_c \, \overline{D}_c$$

5B. Pylon

$$W_{5B} = S_{py} N_e \, (8.0 + 0.0144 \, I_{py})$$

$$\text{where } I_{py} = \frac{W_{dem} \, L_{py}}{H_{py} \, S_{py}}$$

5C. Add for Tail Mounted "S" Duct Nacelle

$$W_{5C} = 3.04 \, [(W_{5A} + W_{5B})/N_e]^{0.893} - (W_{5A} + W_{5B})/N_e$$

6. Propulsion

$$W_6 = W_{6A1} + W_{6A2} + W_{6B} + W_{6C}$$

6A1. Fan Thrust Reverser

$$W_{6A1} = (0.218 \, D_f \, L_{ftr} + 0.0120 \, T_{ftr}) \, N_e$$

Table 3.1 (Continued)

SUMMARY OF WEIGHT ESTIMATING RELATIONSHIPS

6A2. Engine Exhaust Reversers and Nozzles

$W_{6A2} = (0.179\ D_t\ L_{pex} + 0.0389\ T_{ptr})\ N_e$	Cascade or Target Type Reverser with Translating Sleeve
$W_{6A2} = (0.131\ D_t\ L_{pex} + 0.0239\ T_{ptr})\ N_e$	Simple Target Type Reverser with Separate Flow Exhaust Nozzle
$W_{6A2} = (0.105\ D_t\ L_{pex} + 0.0122\ T_{ptr})\ N_e$	Simple Target Type Reverser with Mixed Flow Exhaust Nozzle
$W_{6A2} = (0.113\ D_t\ L_{pex} + 0.0144\ T_{ptr})\ N_e$	Separate Flow Engine Exhaust System Without Thrust Reverser
$W_{6A2} = (0.096\ D_t\ L_{pex} + 0.0094\ T_{ptr})\ N_e$	Short Duct Engine Exhaust System Without Thrust Reverser

6B. Fuel System

$W_{6B} = 2.71\ (L_w\ N_{ft})^{0.956}$	Commercial
$W_{6B} = 0.920\ L_w\ N_{ft}$	Military

6C. Engine Systems

$W_{6C} = 117\ N_e$	Without auto throttle
$W_{6C} = 133\ N_e$	With auto throttle

7,8. Flight Controls and Hydraulics

$W_7 + W_8 = 87.0 + 2.17\ S_{cs}^{0.973}$	Single Hydraulic System
$W_7 + W_8 = 360 + 2.525\ S_{cs}$	Multi-Hydraulic System

Table 3.1 (Continued)

SUMMARY OF WEIGHT ESTIMATING RELATIONSHIPS

7,8. Alternate Flight Controls and Hydraulics Equations

$W_7 + W_8 = 45.0 + 0.269\ (S_w + 1.44\ S_t)^{1.106}$	Single Hydraulic System
$W_7 + W_8 = 45.0 + 1.318\ (S_w + 1.44\ S_t)$	Multi-Hydraulic System $(S_w + 1.44\ S_t) \le 3{,}000$
$W_7 + W_8 = 18.7\ (S_w + 1.44\ S_t)^{0.712} - 1{,}620$	Multi-Hydraulic System $(S_w + 1.44\ S_t) > 3{,}000$

7. Flight Controls

$W_7 = 0.769\ (W_7 + W_8)$	Single Hydraulic System
$W_7 = 0.728\ (W_7 + W_8)$	Multi-Hydraulic System

8. Hydraulics

$W_8 = 0.231\ (W_7 + W_8)$	Single Hydraulic System
$W_8 = 0.272\ (W_7 + W_8)$	Multi-Hydraulic System

9. Electrical

$W_9 = 16.2\ N_p + 110$	Commercial
$W_9 = 0.508\ S_b$	Military $S_b \le 4{,}500$
$W_9 = 0.0919\ S_b + 1{,}870$	Military $S_b > 4{,}500$

10,11, 13. Pneumatic, Air Conditioning and Auxiliary Power

$W_{10} + W_{11} + W_{13} = 26.2\ N_p^{0.944}$	Commercial
$W_{10} + W_{11} + W_{13} = 23.4\ S_b^{0.545}$	Military

10,11. Pneumatic and Air Conditioning

$W_{10} + W_{11} = 13.6\ N_p$	Commercial
$W_{10} + W_{11} = 15.6\ S_b^{0.560}$	Military

Table 3.1 (Continued)

SUMMARY OF WEIGHT ESTIMATING RELATIONSHIPS

10. Pneumatic

$$W_{10} = 0.290\ (W_{10} + W_{11})$$

11. Air Conditioning

$$W_{11} = 0.710\ (W_{10} + W_{11})$$

13. Auxiliary Power

$W_{13} = 26.2\ N_p^{0.944} - 13.6\ N_p$	Commercial
$W_{13} = 23.4\ S_b^{0.545} - 15.6\ S_b^{0.560}$	Military

12. Anti-Icing

$W_{12} = 0.38\ S_w$	Nacelle Air Induction and Misc. Only
$W_{12} = 0.120\ S_w$	Wing Mounted Turbo-fan or Jet Engines Without Tail Anti-Ice
$W_{12} = 0.238\ S_w$	Wing Mounted Turbo-fan or Jet Engines with Tail Anti-Icing
$W_{12} = 0.436\ S_w$	Fuselage and/or Tail Mounted Turbofan Engines with Tail Anti-Icing
$W_{12} = 0.520\ S_w$	Wing Mounted Turboprop Engines with Tail Anti-Icing

14. Furnishings and Equipment

$W_{14} = 62.3\ N_p + 290$	Commercial $N_p \le 80$
$W_{14} = 118.4\ N_p - 4{,}190$	Commercial $N_p > 80$
$W_{14} = 0.650\ S_b$	Military $S_b \le 4{,}500$
$W_{14} = 0.271\ S_b + 1{,}710$	Military $S_b > 4{,}500$

Table 3.1 (Continued)

SUMMARY OF WEIGHT ESTIMATING RELATIONSHIPS

15. Instruments

$W_{15} = 1.872\ N_p + 0.00714\ G + (0.00145\ T + 30)\ N_e + 162$ Commercial

$W_{15} = 0.0540\ S_b + 0.00714\ G + (0.00145\ T + 30)\ N_e + 160$ Military

15A. Fuel Quantity Instruments

$W_{15A} = 0.00714\ G + 34$

15B. Propulsion Instruments

$W_{15B} = (0.00145\ T + 30)\ N_e$

15C. Other Instruments

$W_{15C} = 1.872\ N_p + 128$		Commercial
$W_{15C} = 0.0540\ S_b + 126$		Military

16. Avionics

$W_{16} = N_p + 370$	General Aviation
$W_{16} = 2.8\ N_p + 1,010$	Category I or II Domestic
$W_{16} = 2.8\ N_p + 1,380$	Category I or II Overwater
$W_{16} = 2.8\ N_p + 1,970$	Category III Domestic
$W_{16} = 2.8\ N_p + 2,320$	Category III Overwater
$W_{16} = 0.10\ S_b + 2,330$	Military

17. Load and Handling

$W_{17} = 50$	Commercial
$W_{17} = 130$	Military

Table 3.2

SYMBOLS USED IN WEIGHT ESTIMATING RELATIONSHIPS

Upper Case Symbols

AR - Aspect Ratio

BPR - Bypass Ratio

D - Diameter (inches)

G - Fuel Quantity (gallons)

GLA - Gust Load Alleviation

H - Height (inches)

I - Weight Index

L - Length (inches except feet for wing)

MLA - Maneuver Load Alleviation

N - Number

RSS - Reduced Static Stability

S - Area (square feet)

T - Engine Thrust (lb./engine)

TOGW - Takeoff Gross Weight (lb.)

U - Ultimate Load Factor

W - Weight (lb.)

W/S - Wing loading (lb./ft.^{2})

ZFW - Zero Fuel Weight (lb.)

Lower Case Symbols

a + b - coefficients

b - body

c - cowl

cos - cosine

cs - control surface

dem - demountable weight of power plant

e - engines

f - fan

fex - fan exhaust ducting including bifurcated ducts and outer cowl

ft - fuel tanks

ftr - fan thrust reverser

h - horizontal

i - lip to engine front face

p - passenger

ptr - engine exhaust thrust reverser

py - pylon

pex - primary exhaust nozzle

s - landing gear struts

t - tail or turbine exhaust flange

t/c - average thickness to chord ratio

v - vertical tail

w - wing

λ - taper ratio (tip chord/root chord)

Ω C/4 - sweep angle of quarter chord equations for the cowling and pylon). Likewise, separate WERs were developed for small and large and for commercial and military transports for cases where a single WER was not applicable to all types of aircraft. For several systems, alternative equations are provided. Thus, depending upon the design information available and other factors explained in Section 5, a choice may be made regarding which equation to use.

The estimating relationships can be used for conceptual studies where approximate weight estimates are required, but where limited design data are available. These estimating relationships can also be used as the basis for determining the weights required for making airframe cost estimates using the cost estimating relationships discussed in Sections 2 and 4 of this report.

B. SUMMARY OF WEIGHT DATA

System weight data are given in Tables 3.3 and 3.4 for 19 commercial and 7 military transports, respectively. These data, as well as more detailed data, were used in the derivation of the WERs presented in Table 3.1. Three recent study aircraft are included in order to provide a broader, more comprehensive data base. These are the MDAT, SCAT-15, and AST(M).*

The sources for the data tabulated in Tables 3.3 and 3.4 are given in Table 3.5 together with notation of any adjustments that were made to ensure comparability for all aircraft.

C. APPLICATIONS OF THE WEIGHT ESTIMATING RELATIONSHIPS

Weight estimates have been made for the DC-10-10, C-141A and F-28 using the equations in Table 3.1. As mentioned in Section 2B, these aircraft were selected as examples because of their great diversity. The results are presented together with the equations and variables used and the actual weights in Tables 3.6, 3.7 and 3.8, respectively.

* The MDAT is the Medium Density Air Transport, SCAT is the Supersonic Cruise Air Transport and the AST(M) is the Advanced STOL Transport (Medium).

Table 3.3

SUMMARY WEIGHT STATEMENT - COMMERCIAL AIRCRAFT

Aircraft System	CITATION-500	MDAT-30	MDAT-50	F-28	MDAT-70	DC-9-10	BAC-111	DC-9-30	737-200	727-100
Wing System	1,020	3,143	4,360	7,526	5,910	9,366	9,817	11,391	11,164	17,682
Tail System	288	1,010	1,193	1,477	1,505	2,619	2,470	2,790	2,777	4,148
Body System	930	4,276	5,692	6,909	7,118	9,452	11,274	11,118	11,920	17,589
Alighting Gear System	425	1,379	1,874	2,564	2,440	3,640	3,465	4,182	4,038	7,244
Nacelle System	241	948	1,294	866	1,684	1,462	1,191	1,462	1,515	2,226
Propulsion System (less Dry Engine)	340	1,140	1,338	988	1,702	1,478	1,788	2,190	1,721	3,052
Flight Controls System (less Auto Pilot)	196	600	699	1,404	805	1,102	1,655	1,434	2,325	2,836
Auxiliary Power System	0	343	400	320	460	805	719	817	855	0
Instrument System	76	300	300	267	300	490	504	575	518	723
Hydraulic and Pneumatic System	94	257	300	406	345	681	1,391	753	835	1,054
Electrical System	361	617	825	953	1,040	1,631	1,610	1,715	2,156	2,988
Avionics System (incl. Auto Pilot)	321	586	586	923	586	1,039	1,368	1,108	1,100	1,844
Furnishings and Equipment System	794	2,657	3,548	3,535	4,772	6,690	7,771	8,594	9,119	11,962
Air Conditioning System	188	325	435	520	550	1,016	1,062	1,110	1,084	1,526
Anti-icing System	101	384	448	520	511	472	234	474	113	639
Load and Handling System	2	20	20	—	20	19	9	57	—	15
Empty Weight (less Dry Engine)	5,377	17,985	23,312	29,178	29,748	41,962	46,328	49,770	51,240	75,528
Dry Engine Weight	1,002	2,480	3,373	4,327	4,392	6,113	5,434	6,160	6,212	9,322
Empty Weight (M.E.W.)	6,379	20,465	26,685	33,505	34,140	48,075	51,762	55,930	57,452	84,850
Takeoff Gross Weight	11,650	34,480	46,850	62,000	61,000	86,300	99,650	108,000	104,000	161,000

Table 3.3 (CONTINUED)

SUMMARY WEIGHT STATEMENT - COMMERCIAL AIRCRAFT

Aircraft System	727-200	707-320	DC-8-55	DC-8-62	DC-10-10	L-1011	DC-10-40	747	SCAT-15*
Wing System	18,529	28,647	34,909	36,247	48,990	47,401	57,748	88,741	83,940
Tail System	4,142	6,004	4,952	4,930	13,657	8,570	14,454	11,958	8,590
Body System	22,415	22,299	22,246	23,704	44,790	49,432	46,522	68,452	54,322
Alighting Gear System	7,948	11,216	11,682	11,449	18,581	19,923	25,085	32,220	28,720
Nacelle System	2,225	3,176	4,644	6,648	8,493	8,916	9,328	10,830	15,650
Propulsion System (less Dry Engine)	3,022	5,306	9,410	7,840	7,673	8,279	13,503	9,605	6,310
Flight Controls System (less Auto Pilot)	2,984	2,139	2,035	2,098	5,120	5,068	5,188	6,886	10,777
Auxiliary Power Plant System	849	0	0	0	1,589	1,202	1,592	1,797	--
Instrument System	827	550	1,002	916	1,349	1,016	1,645	1,486	3,400
Hydraulic and Pneumatic Group	1,147	1,557	2,250	1,744	4,150	4,401	4,346	5,067	10,670
Electrical System	2,844	3,944	2,414	2,752	5,366	5,490	5,293	5,305	6,062
Avionics System (incl. Auto Pilot)	1,896	1,815	1,870	2,058	2,827	2,801	3,186	4,134	4,178
Furnishings and Equipment System	14,702	16,875	15,884	15,340	38,072	32,829	33,114	48,007	20,615
Air Conditioning System	1,802	1,602	2,388	2,296	2,386	3,344	2,527	3,634	2,820
Anti-icing System	666	626	794	673	416	296	555	413	210
Load and Handling System	19	--	55	54	62	--	62	228 -896**	--
Empty Weight (less Dry Engine)	86,017	105,756	116,535	118,749	203,521	198,968	224,148	297,867	256,204
Dry Engine Weight	9,678	19,420	16,936	17,316	23,229	30,046	25,587	35,700	45,020
Empty Weight (M.E.W.)	95,695	125,176	133,471	136,065	226,750	229,014	249,735	333,567	301,224
Takeoff Gross Weight	175,000	312,000	325,000	335,000	430,000	430,000	565,000	775,000	631,000

*Estimated

**Manufacturing adjustment.

Table 3.4

SUMMARY WEIGHT STATEMENT - MILITARY AIRCRAFT

	C-130A	C-130E	KC-135A	C-133B	C-141A	C-5A	AST(M)*
Wing System	10,593	11,647	24,719	27,064	34,262	81,782	20,560
Tail System	3,190	3,409	4,958	6,147	5,745	12,344	8,730
Body System	14,045	14,241	17,850	32,119	28,578	115,216	29,025
Alighting Gear System	4,441	5,077	10,698	11,062	10,529	37,628	9,360
Nacelle System	2,685	2,674	2,547	3,939	5,63[illegible]	8,472	4,711
Propulsion System (less Dry Engines)	6,427	9,489	6,489	10,719	5,780	6,813	5,761
Flight Controls System (less Autopilot)	1,228	1,444	1,749	1,385	3,448	6,936	4,668
Auxiliary Power Plant System	482	460	0	1,584	635	1,067	651
Instrument System	559	550	382	563	899	734	994
Hydraulic and Pneumatic System	922	875	1,393	1,526	2,163	4,317	2,465
Electrical System	1,680	2,289	2,333	2,526	3,015	3,300	2,068
Avionics System (incl. Autopilot)	2,201	2,657	2,231	2,630	2,938	4,130	2,919
Furnishings and Equipment System	3,265	4,770	1,374	4,549	4,362	7,811	6,870
Airconditioning System	1,108	1,064	743	1,746	1,547	2,602	906
Anti-icing System	932	785	350	1,575	598	233	552
Load and Handling System	61	61	--	105	104	273	150
Empty Weight (less Dry Engine)	53,819	61,492	77,816	109,239	110,233	293,658	100,390
Dry Engine Weight	6,680	7,195	14,862	11,186	18,407	28,999	12,280
Empty Weight (M.E.W.)	60,499	68,687	92,678	120,425	128,640	322,657	112,670
Takeoff Gross Weight	108,000	155,000	275,000	286,000	316,100	728,000	163,500

*Estimated

Table 3.5

WEIGHT DATA SOURCES AND ADJUSTMENTS

Aircraft	Data Source	MEW Adjustments
CITATION-500	Cessna WB500-3, July 1973	Removed 24 lb. lounge seat, added 120 lb. of pax seats and transferred 36 lb. of exterior paint from operator items weight to furnishings and equipment.
MDAT-30	NASA CR 137604, March 1975	
MDAT-50	NASA CR 137604, March 1975	
F-28	DAC Data Center No. 242050, Oct. 1968	
MDAT-70	NASA CR 137604, March 1975	
DC-9-10	DAC Control Book, Feb. 1970	Added 240 lb. of pax seats to furnishings and equipment.
BAC-111	DAC Data Center No. 963-80	Transferred to operator items weight as follows: residual fuel from power plant system - 4 lb. engine oil from power plant system - 56 lb. unusable fuel from fuel system -224 lb. engine oil from aux. power system - 11 lb. lavatory fluids from toilet system - 22 lb. water from domestic water system -210 lb. escape slides from miscellaneous weight - 42 lb. Total adjustment -569 lb.
DC-9-30	DAC Control Book, Sept. 1969	Added 480 lb. of seat weight to furnishings and equipment.
737-200	BAC Weights Research Study No. 25, Sept. 1968	Added 480 lb. of seat weight, and 842 lb. of galley weight (transferred from operator items weight) to furnishings and equipment.
727-100	BAC 68-025, Feb. 1968	Added 1,320 lb. of seat weight, and 600 lb. of galley weight (transferred from operator items weight) to furnishings and equipment
727-200	BAC Control Book, May 1974	Added 720 lb. of pax seats, transferred 2,246 lb. of galley structure and 66 lb. of emergency equipment from operator items to furnishings and equipment.
707-320	DAC Data Center No. 209380	Added 1,410 lb. of seat weight, 900 lb. of galley weight (transferred to operator items weight) and removed 363 of liferaft weight from furnishings and equipment.
DC-8-55	DAC Control Book	Added 1,290 lb. of seat weight to furnishings and equipment.

Table 3.5 (Continued)

WEIGHT DATA SOURCES AND ADJUSTMENTS

Aircraft	Data Source	MEW Adjustments
DC-8-62	DAC Control Book, Apr. 1968	Added 810 lb. of seat weight to furnishings and equipment.
DC-10-10	DAC Control Book, July 1973	Added 2,28[illegible] lb. of seat weight to furnishings and equipment.
L-1011	DAC Data Center No. 962360, Jan. 1972	Added 2,220 lb. of seat weight and 4,011 lb. of galley weight (transferred from operator items weight) to furnishings and equipment.
DC-10-40	DAC Control Book, Aug. 1973	Added 1,260 lb. of seat weight to furnishings and equipment.
747	BAC Control Book, Jun. 1974	Added 6,466 lb. of seat weight and 7,900 lb. of galley weight (transferred from operator items weight) to furnishings and equipment. Transferred 681 lb. of life rafts from furnishings and equipment to operator items weight.
SCAT-15	Boeing D6A11666-1, June 1969	Removed 2,240 of cargo container and added 2,124 lb. of galley weight (transferred from operator items weight) to furnishings and equipment.
C-130A	LAC ER-3121, Feb. 1958	None
C-130E	LAC ER-6287, Oct. 1965	None
KC-135A	BAC D6,2743, June 1957	None
C-133B	DAC LB-30378, Apr. 1961	None
C-141A	LAC ER5020, May 1964	None
C-5A	LAC LG1US54-11-1, May 1970	None
AST(M)	DAC MDC J5652	Removed 940 lb. of life rafts, life preservers, and parachutes from furnishings and equipment.

Table 3.6

DC-10-10 WEIGHT ESTIMATE

System / Equation	Variables Used	Estimated Weight	Actual Weight	Percent Difference
1. Wing				
$W_1 = .930\ I_w + 6.44\ S_w + 390$	$I_w = 24{,}600,\ S_w = 3{,}550$	46,130	48,990	- 5.8
2. Tail				
$W_2 = 5.03\ S_t$	$S_t = 1{,}625$	8,174	9,798	-16.6
3. Body				
$W_3 = 161\ N_p - 5{,}110$	$N_p = 330$	48,020	44,790	+ 7.2
4. Alighting Gear				
$W_4' = 0.0440\ TOGW - 672$	$TOGW = 430{,}000$	18,248	18,581	- 1.8
5. Nacelle				
$W_5 = W_{5A} + W_{5B}$		(6,453)	(8,493)	-24.0
Cowl				
$W_{5A} = 0.0415\ N_e\ I_c$	$N_e = 3,\ I_c = 26{,}280$	3,272	3,980	-17.8
Pylon				
$W_{5B} = S_{py}\ N_e\ (8.0 + 0.0144\ I_{py})$	$S_{py} = 62.5,\ N_e = 3,\ I_{py} = 623$	3,181	4,513	-29.5
6. Propulsion				
$W_6 = W_{6A1} + W_{6A2} + W_{6B} + W_{6C}$		(7,646)	(7,673)	0.4
Fan Thrust Reverser				
$W_{6A} = (0.218\ D_f\ L_{ftr} + 0.0120\ T_{ftr})\ N_e$	$D_f = 93,\ L_{ftr} = 46.0,\ T_{ftr} = 34{,}200,\ N_e = 3$	4,029	4,014	+ 0.4
Engine Exhaust Thrust Reverser				
$W_{6A2} = (0.179\ D_t\ L_{pex} + 0.0389\ T_{ptr})\ N_e$	$D_t = 50.0,\ L_{pex} = 25.0,\ T_{ptr} = 5{,}800,\ N_e = 3$	1,348	1,368	- 1.5

Table 3.6 (Continued)

DC-10-10 WEIGHT ESTIMATE

System / Equation	Variables Used	Estimated Weight	Actual Weight	Percent Difference
6. Propulsion (Cont'd.)				
Fuel System				
$W_{6B} = 2.71\ (L_w\ N_{ft})^{0.956}$	$L_W = 155.4,\ N_{ft} = 6$	1,870	1,850	+ 1.1
Engine Systems				
$W_{6C} = 133\ N_e$	$N_e = 3$	399	441	- 9.5
7, 8. Flight Controls and Hydraulics				
$W_7 + W_8 = 360 + 2.525\ S_{cs}$	$S_{cs} = 3{,}028$	(8,006)	(7,483)	+ 7.0
7. Flight Controls				
$W_7 = 0.728\ (W_7 + W_8)$	$W_7 + W_8 = 8{,}006$	5,828	5,120	+13.8
8. Hydraulics				
$W_8 = 0.272\ (W_7 + W_8)$	$W_7 + W_8 = 8{,}006$	2,178	2,363	- 7.8
9. Electrical				
$W_9 = 16.2\ N_p + 110$	$N_p = 330$	5,456	5,366	+ 1.7
10, 11. Pneumatic, Air Conditioning				
$W_{10} + W_{11} = 13.6\ N_p$	$N_p = 330$	(4,488)	(4,173)	+ 8.0
10. Pneumatic				
$W_{10} = 0.290\ (W_{10} + W_{11})$	$W_{10} + W_{11} = 4{,}488$	1,266	1,787	-29.2
11. Air Conditioning				
$W_{11} = 0.710\ (W_{10} + W_{11})$	$W_{10} + W_{11} = 4{,}488$	3,222	2,386	+35.1
12. Anti-Icing				
$W_{12} = 0.120\ S_w$	$S_w = 3{,}550$	426	416	+ 2.4
13. Auxiliary Power				
$W_{13} = 26.2\ N_p^{0.944} - 13.6\ N_p$	$N_p = 330$	1,760	1,589	+10.8

Table 3.6 (Continued)

DC-10-10 WEIGHT ESTIMATE

System / Equation	Variables Used	Estimated Weight	Actual Weight	Percent Difference
14. Furnishings & Equipment				
$W_{14} = 118.4\ N_p - 4{,}190$	$N_p = 330$	34,882	38,072	- 8.4
15. Instruments				
$W_{15} = 1.872\ N_p + 0.00714\ G + (0.00145\ T + 50)\ N_e \div 162$	$N_p = 330$, $G = 21{,}672$, $T = 40{,}000$, $N_e = 3$	1,198	1,349	-11.2
16. Avionics				
$W_{16} = 2.8\ N_p + 1{,}970$	$N_p = 330$	2,894	2,827	+ 2.4
17. Load and Handling				
$W_{17} = 50$		50	62	-19.4
Total		193,831	199,662	- 2.9

Table 3.7

C-141 WEIGHT ESTIMATE

System / Equation	Variables Used	Estimated Weight	Actual Weight	Percent Difference
1. Wing				
$W_1 = 0.930\ I_w + 6.44\ S_w + 390$	$I_w = 16{,}232,\ S_w = 3{,}000$	34,806	34,262	+ 1.6
2. Tail				
$W_2 = 6.39\ S_t$	$S_t = 899$	5,745	5,745	0
3. Body				
$W_3 = 0.467\ S_b^{1.277}$	$S_b = 5{,}096$	25,319	28,578	-11.4
4. Alighting Gear				
$W_4' = 0.0439\ TOGW - 2{,}050$	$TOGW = 316{,}100$	11,827	10,529	+12.3
5. Nacelle				
$W_5 = W_{5A} + W_{5B}$		(5,042)	(5,630)	-10.4
Cowl				
$W_{5A} = 0.0415\ N_e\ I_c$	$N_e = 4,\ I_c = 15{,}695$	2,605	3,352	-22.3
Pylon				
$W_{5B} = S_{py}\ N_e\ (8.0 + 0.0144\ I_{py})$	$S_{py} = 52.0,\ N_e = 4,\ I_{py} = 258$	2,437	2,278	+ 7.0
6. Propulsion				
$W_6 = W_{6A2} + W_{6B} + W_{6C}$		(5,236)	(5,780)	- 9.4
Thrust Reverser				
$W_{6A2} = (0.179\ D_t\ L_{pex} + 0.0389\ T_{ptr})\ N_e$	$D_t = 41.0,\ L_{pex} = 0.774,\ T_{ptr} = 21{,}000,\ N_e = 4$	3,290	3,294	- 0.1
Fuel System				
$W_{6B} = 0.920\ L_w\ N_{ft}$	$L_w = 160.7,\ N_{ft} = 10$	1,478	1,566	- 5.6
Engine System				
$W_{6C} = 117\ N_e$	$N_e = 4$	468	920	-49.1
7, 8. Flight Controls and Hydraulics				
$W_7 + W_8 = 360 + 2.525\ S_{cs}$	$S_{cs} = 1{,}689$	(4,625)	(4,952)	- 6.6

Table 3.7 (Continued)

C-141 WEIGHT ESTIMATE

System / Equation	Variables Used	Estimated Weight	Actual Weight	Percent Difference
7. Flight Controls				
$W_7 = 0.728\ (W_7 + W_8)$	$(W_7 + W_8) = 4,625$	3,367	3,448	- 2.3
8. Hydraulics				
$W_8 = 0.272\ (W_7 + W_8)$	$(W_7 + W_8) = 4,625$	1,258	1,504	-16.4
9. Electrical				
$W_9 = 0.0919\ S_b + 1,872$	$S_b = 5,096$	2,340	3,015	-22.4
10, 11. Pneumatic, Air Conditioning				
$W_{10} + W_{11} = 15.6\ S_b^{0.560}$	$S_b = 5,096$	(1,859)	(2,206)	-15.7
10. Pneumatic				
$W_{10} = 0.290\ (W_{10} + W_{11})$	$(W_{10} + W_{11}) = 1,859$	524	659	-20.4
11. Air Conditioning				
$W_{11} = 0.710\ (W_{10} + W_{11})$	$(W_{10} + W_{11}) = 1,859$	1,335	1,547	-13.7
12. Anti-Icing				
$W_{12} = 0.238\ S_w$	$S_w = 3,000$	714	598	+19.4
13. Auxiliary Power				
$W_{13} = 23.4\ S_b^{0.545} - 15.6\ S_b^{0.560}$	$S_b = 5,096$	594	635	- 6.4
14. Furnishings & Equipment				
$W_{14} = 0.271\ S_b + 1,710$	$S_b = 5,096$	3,091	4,362	-29.1
15. Instruments				
$W_{15} = 0.0540\ S_b + 0.00714G + (0.00145T + 30)\ N_e + 160$	$S_b = 5,096,\ G = 23,594,\ T = 21,000,\ N_e = 4$	845	899	- 6.0
16. Avionics				
$W_{16} = 0.10\ S_b + 2,330$	$S_b = 5,096$	2,840	2,938	- 3.3
17. Load and Handling				
$W_{17} = 130$		130	104	+21.2
Total		105,013	110,233	- 4.7

Table 3.8

F-28 WEIGHT ESTIMATE

System / Equation	Variables Used	Estimated Weight	Actual Weight	Percent Difference
1. Wing $W_1 = 4.24\ I_w + 0.57\ S_w$	$I_w = 1,656$, $S_w = 822$	7,490	7,526	[illegible]
2. Tail $W_2 = 6.39\ S_t$	$S_t = 342$	2,185	1,477	+48.0
3. Body $W_3 = 110\ N_p$	$N_p = 60$	6,600	6,909	- 4.5
4. Alighting Gear $W_4' = 0.0395\ TOGW$	TOGW = 62,000	2,449	2,564	- 4.5
5. Nacelle $W_5 = W_{5A} + W_{5B}$	NA	—	866	—
Cowl $W_{5A} = 0.0415\ N_e\ I_c$	NA	—	—	—
Pylon $W_{5B} = S_{py}\ N_e\ (8.0 + 0.0144\ I_{py})$	NA	—	—	—
6. Propulsion $W_6 = W_{6A1} + W_{6A2} + W_{6B} + W_{6C}$	NA	—	988	—
Fan Thrust Reverser $W_{6A1} = (0.218\ D_f\ L_{ftr} + 0.0120\ T_{ftr})\ N_e$	NA	—	—	—
Engine Exhaust Thrust Reverser $W_{6A2} =$	NA	—	—	—
Fuel System $W_{6B} = 2.71\ (L_w\ N_{ft})^{0.956}$	NA	—	—	—
Engine System $W_{6C} = 133\ N_e$	NA	—	—	—

Table 3.8 (Continued)

F-28 WEIGHT ESTIMATE

System / Equation	Variables Used	Estimated Weight	Actual Weight	Percent Difference
7, 8. Flight Controls and Hydraulics				
$W_7 + W_8 = 45.0 + 1.318 (S_w + 1.44 S_t)$	$S_w = 822$, $S_t = 485$	(2,049)	(1,746)	+17.3
7. Flight Controls				
$W_7 = 0.728 (W_7 + W_8)$	$(W_7 + W_8) = 2,048$	1,492	1,404	+ 6.2
8. Hydraulics				
$W_8 = 0.272 (W_7 + W_8)$	$(W_7 + W_8) = 2,048$	557	342	+63.0
9. Electrical				
$W_9 = 16.2 N_p + 110$	$N_p = 60$	1,082	953	+13.5
10, 11. Pneumatic, Air Conditioning				
$W_{10} + W_{11} = 13.6 N_p$	$N_p = 60$	(816)	(584)	+39.7
10. Pneumatic				
$W_{10} = 0.290 (W_{10} + W_{11})$	$(W_{10} + W_{11}) = 816$	230	64	+359.5
11. Air Conditioning				
$W_{11} = 0.710 (W_{10} + W_{11})$	$(W_{10} + W_{11}) = 816$	586	520	+12.7
12. Anti-Icing				
$W_{12} = 0.238 S_w$	$S_w = 822$	196	520	-37.6
13. Auxiliary Power				
$W_{13} = 26.2 N_p^{0.944} - 13.6 N_p$	$N_p = 60$	434	320	+35.6
14. Furnishings and Equipment				
$W_{14} = 62.3 N_p + 290$	$N_p = 60$	4,028	3,535	+13.9
15. Instruments				
$W_{15} = 1.872 N_p + 0.00714G + (0.00145T + 30) N_e + 162$	NA	—	267	—
16. Avionics				
$W_{16} = 2.8 N_p + 1.010$	$N_p = 60$	1,178	923	+27.6

Table 3.8 (Continued)

F-28 WEIGHT ESTIMATE

System / Equation	Variables Used	Estimated Weight	Actual Weight	Percent Difference
17. Load and Handling				
$W_{17} = 50$		50	D	—
Total*		28,557	27,057	+ 5.5

* Less nacelle, propulsion and instrument systems.

When the total estimated weights were compared with the total actual weights it was found that the DC-10-10 and C-141A were under-estimated by 2.9 and 4.7 percent, respectively. The F-28 was over-estimated by 5.5 percent. Note that in the case of the F-28, certain design data were not available so that estimates could not be made for the nacelle, propulsion and instrument systems and the actual total was adjusted to exclude them. However, these systems are only 7 percent of the actual weight. The DC-10-10 estimated weights are significantly low for the tail because of the double hinged rudder and the tail mounted engine. The estimated weights are low for the nacelle because the pylons are extraordinarily heavy due to the use of stiffening material to reduce nacelle flutter. For the C-141, the furnishings and equipment were significantly underestimated. The WER for furnishings and equipment on military aircraft does not include the weight of a number of items such as troop seats, oxygen system and litters and supports. When the weight of these items is taken into account, the actual and estimated weights show good agreement. Several significant differences were noted in comparing estimated and actual weights for the F-28. These differences could not be explained, however, because adequate design information was not available.

SECTION 4

DETAILED SYSTEM COST ANALYSIS

The production cost estimating relationships (CERs) derived in this study were presented in Table 2.1 of Section 2. In this section, the basis for each CER is discussed in detail. CERs were derived for each aircraft system or major components of several of the systems. Each system, or logical grouping of systems in several cases, is discussed in turn. The system is first described in detail; these descriptions are in accordance with Military Standard 1374 except as noted.* Then, the cost data for the system is presented, and the derivation of the CER or CERs is explained in detail. It should be noted that much of the cost data are presented in general terms since they are considered proprietary by the aircraft manufacturers or subcontractors. Finally, for each system, or system grouping, emerging technology is discussed as appropriate.

All costs are given in constant 1975 dollars. Most of the subcontractor data are recent and were assumed to be in 1975 dollars. However, the historical data used, primarily that data documented in Reference 6, were normalized by means of the factors in Table 4.1.** All costs are cumulative average costs for 100 units unless otherwise indicated. A quantity scaling factor or "learning curve" was used to adjust to 100 units.*** For structure, an 86 percent learning curve was used based on C-5 and C-141 data.(6) For instruments and avionics an 88 percent learning curve was used base on a Rand Corporation study.(9) For all other systems a 94 percent learning curve was used based on C-5 and C-141 data.(6)

* For convenience, all system descriptions presented in this section are summarized in Appendix C.

** Reference 6 normalized costs to 1973 dollars. For this report, these costs were adjusted from 1973 dollars to 1975 dollars using factors of 1.249 for airframe and 1.131 for avionics. These factors are different from those indicated in Table 4.1 since Reference 6 used projected escalation rates which have been corrected in Table 4.1.

***These learning curves are incorporated in the CER equations in Table 2.1.

Table 4.1

ECONOMIC ESCALATION FACTORS*

Calendar Year	Airframe Production	Avionics Production**
1953	3.074	2.575
1954	3.055	2.559
1955	3.016	2.526
1956	2.854	2.390
1957	2.665	2.233
1958	2.573	2.155
1959	2.471	2.069
1960	2.377	1.994
1961	2.292	1.926
1962	2.231	1.855
1963	2.163	1.796
1964	2.098	1.737
1965	2.003	1.688
1966	1.900	1.624
1967	1.807	1.532
1968	1.709	1.441
1969	1.585	1.363
1970	1.483	1.295
1971	1.409	1.234
1972	1.309	1.176
1973	1.202	1.123
1974	1.093	1.062
1975	1.000	1.000

* The factors apply to the mid-year.

**Also used for instruments.

Sources: 1953 to 1957: DoD Price Indicies, Revised 22 Nov. 71, OSD (PA&E).

1958 to 1971: Historical and Forecasted Aeronautical Cost Indicies, USAF/ASD Cost Report #110, January 1973.

1972 to 1975: Aeronautical Economic Escalation Indicies, USAF/ASD Cost Report #110B, July 1975.

A. WING, TAIL AND BODY SYSTEMS

The wing, tail and body structural systems are considered together for they have similar designs and use similar materials and methods of fabrication. Although the wing, tail and body account for about 40 percent of the total cost of a transport aircraft, a relatively small effort was devoted to the analysis of their costs because previous research had been conducted in this area. Furthermore, the principal objective of this study was to develop CERs for the non-structural systems. Some new data were obtained for the wing, tail and body and were compared with the previous research. Then, CERs were developed that were compatible with those derived for the other systems.

Systems Descriptions

The wing system consists of the wing box structure, leading and trailing edge structure and leading and trailing edge control surfaces. Actuation for the control surfaces is accounted for in the flight controls system. The wing carry through structure is included with the wing system. Systems such as the fuel system, hydraulic system and anti-ice system are included with their respective functional systems. For wing mounted landing gear designs, the wing bulkhead, trunnion attach fitting and auxiliary spar structure required to distribute landing gear loads in the wing and to transfer these loads to the fuselage are included with the alighting gear system. All wing attach bulkheads located in the fuselage are included in the body system.

The tail system or empennage is defined similar to that of the wing. The horizontal tail includes all carry through structure, but the vertical tail usually terminates at the fuselage loft line (top of fuselage). Fairings fillets and the fin are included with the tail system.

The body system consists of fuselage shell structure, door and window frames, doors, windows, floors, bulkheads, cockpit windshield, radome and tailcone. Door actuation mechanisms and airstairs are also included with the body system. For the C-5A and AST(M), the body system includes the cargo loading system since it is built in integral with the floor structure. Sidewall insulation and paneling as well as cockpit instrument panels and consoles are considered part of the furnishings and equipment system.

Systems Costs

Subcontractor cost information was available for several military transports.[6] Because this information is considered proprietary to the contractors, it can be discussed only in general terms. Reasonably complete wing subcontractor cost data were available only for the C-141 and C-5 and ranged from $39 to 43 per pound for wing weights of 34,000 and 82,000 pounds. For each of these two aircraft, several subcontractors provided wing parts amounting to 88 and 95 percent of the total wing weight. The same cost per pound was assumed to apply to the balance of the wing parts for which no cost data were available. Tail subcontractor cost data were obtained for the C-5, C-141, KC-135 and C-130 and ranged from $60 to 89 per pound for tail weights of 3,000 to 12,000 pounds. For each of these four aircraft, a single subcontractor supplied essentially the entire tail system. The only subcontractor data for the body was a cost of $81 per pound for one section of the KC-135 body which represented 27 percent of the total body weight.

In order to arrive at a total system level cost, the wing and body subcontractor costs were adjusted by an approximate factor of 1.33 as discussed in Section 2C. In the case of the tail, the subcontractor cost included system level assembly, hence a factor of 1.21 was applied to those costs.

When these adjusted subcontractor cost data are plotted as a function of weight, a reduction in cost per pound is observed as weight increases. For example, the wing and tail subcontractor data for the C-141 and C-5 show a reduction in cost per pound as weight increases which can be stated as follows: as weight is doubled the cost per pound is reduced to 93 percent for the wing and 92 percent for the tail.* This reduction of structural cost per pound with increased weight, which will be referred to as "weight scaling" for convenience, is commonly experienced by aircraft manufacturers. In discussions with three aircraft manufacturers, two indicated that an 80 percent slope (as weight is doubled the cost is reduced to 80 percent) reflected their experience and the third indicated that a 90 percent slope was typical. Although the wing and tail subcontractor data for the C-141 and C-5 discussed above indicate 92 and 93 percent slopes, these data are probably not typical since expensive methods were used for saving weight in the C-5 (e.g., chemical milling) which resulted in unusually high costs per pound for the C-5 wing and tail. Also, wide body transports such as the C-5 may exhibit diseconomies of scale (e.g., increased difficulty in handling parts). Based on the discussions with the aircraft manufacturers, a weight scaling slope of 85 percent is assumed in this study for the wing, tail and body.

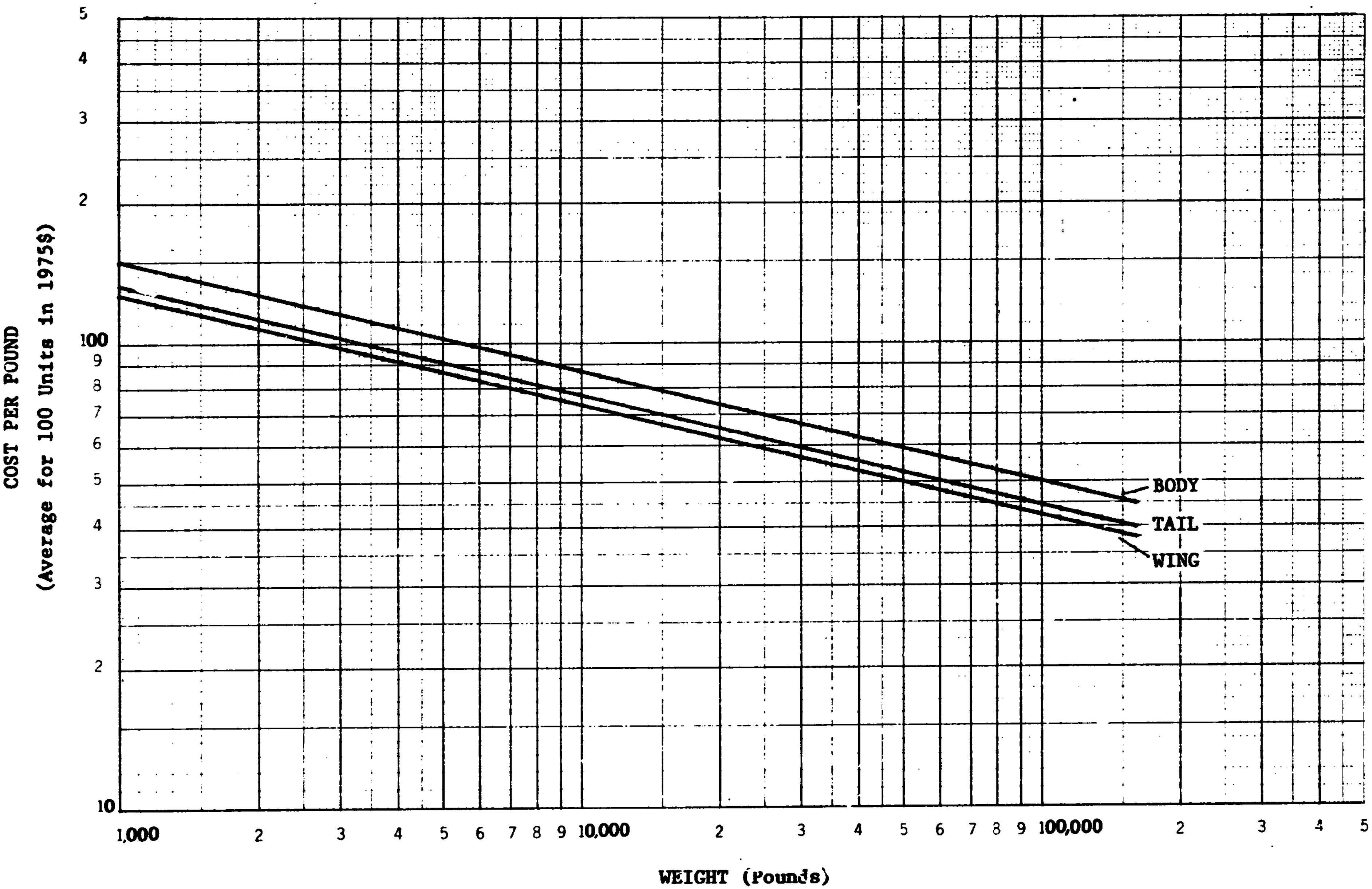
The cost estimating relationships for the wing and tail shown in Figure 4.1 are based on the subcontractor data and an 85 percent weight scaling slope. The actual subcontractor data is not shown in Figure 4.1 because they are considered proprietary. The CER for the body is discussed later.

The results from a General Dynamics study were used to provide additional information on wing, tail and body costs.[4] The cost estimating relationships developed by General Dynamics were for first unit costs in 1970 dollars. To make these data comparable with the adjusted subcontractor costs discussed above, they were adjusted to cumulative average cost per pound for 100 units (CAC_{100}) and 1975 dollars. Costs for sustaining engineering, sustaining tooling, and profit were also

* This reduction in cost with increased weight can be interpreted in the same manner as a learning curve, which shows a reduction in cost with increased quantity.

Figure 4.1

WING, TAIL AND BODY CERs



added. A learning curve slope of 86 percent was indicated by the C-141 and C-5 data and was applied.[6] The economic escalation factors from Table 4.1 were used to adjust the data to 1975 dollars. The adjusted General Dynamics estimating relationships for the wing and tail differ by from 0 to 23 percent from the CERs shown in Figure 4.1. It is not clear how comparable the General Dynamics costs are to the subcontract costs collected nor is it certain that the learning curve slope of 86 percent used to adjust from first unit cost to CAC_{100} is appropriate for the General Dynamics data. Even a small change in the learning curve slope would introduce a large change in the CAC_{100}. For example, a one percent change in slope introduces an eight percent change in CAC_{100}. Given these uncertainties, the General Dynamics estimating relationships for wing and tail show good agreement with those developed from the subcontract data.

Since the single subcontractor data point for the body was of limited value, the ratio between the General Dynamics cost estimating relationships for body and wing (1.19) was applied to the wing CER to provide an approximate CER for the body.

Confidence values* for the wing, tail, and body of 8.0, 9.0, and 7.0, respectively, were assigned.

Emerging Technologies

Engineering studies and development programs have demonstrated that substantial weight savings can be realized through the use of composite materials. Until experience is gained with the manufacturer of aircraft structures utilizing composite materials, the effect of composite materials on the cost of aircraft structures is uncertain. However, some estimates made for the substitution of composite materials in several places on the F-16 and B-1 indicate that both weight and cost may typically be reduced in about the same proportions.[10] Thus, the total cost would be reduced but the cost per pound would be about the same as for current structures.

* See discussion in Section 2C.

B. ALIGHTING GEAR SYSTEM

System Description

The alighting gear system consists of all items associated with main and nose gears. This includes landing gear structure which is made up of struts, side and drag braces, bogie beams and/or axles, trunnions, attachment fittings and wing attachment bulkheads, and extra load-path material in the wing for wing mounted gears. The alighting gear controls comprise the components for such functions as retraction, braking and steering. The controls also include cables, wires, or lines from the cockpit controls to the landing gear. In addition, the alighting gear system includes the rolling items of wheels, brakes and tires.

System Cost

Alighting gear cost information may be conveniently grouped into four distinct categories: structure, controls, wheels and brakes, and tires. Detailed subcontractor and vendor cost information was available for the C-5, C-141, KC-135 and C-130.[6] Subcontractor cost information was also obtained for the structure for the DC-10, 727, and 747. Alighting gear controls cost data were obtained from several sources. Because all of the cost information is considered proprietary, it can be discussed only in general terms.

The principal alighting gear subcontractors supply items which comprise approximately 84 percent of total alighting gear structural weight for each of the four military transport aircraft. It appears that these subcontractors also supply about the same percentage of the total alighting gear structure for commercial aircraft. As in the case of the wing and tail, the same cost per pound was assumed to apply to the balance of the alighting gear structural components for which no cost data were available. Alighting gear structural costs ranged from $76 to 31 per pound for weights of 1,400 to 20,000 pounds.

Alighting gear controls cost per pound figures are shown in Table 4.2. They are based on the flight controls system component costs discussed in Section 4E as they are similar in design and construction. The average cost per pound is $78. This value does not appear to vary with the total weight of the controls.

Cost data for the wheels and brakes were obtained for the C-5, C-141, and KC-135. The C-5 components were unusually expensive. This was probably due in large part to the use of beryllium brakes which save weight but increase unit costs. The C-5 data, therefore, were not considered. For the other two aircraft, wheel and brake costs ranged from $10 to 14 per pound for weights from 2,100 to 2,600 pounds.

Tires are a negligible portion of the total alighting gear system cost. For example, the C-141 tires total $2,600 per aircraft or $2.10 per pound. For the C-130, the tires are $1,300 per aircraft or $1.50 per pound.

In order to arrive at a total system level cost, the costs discussed above, except for tires, were adjusted by an approximate factor of 1.33 as discussed in Section 2C. Tires were adjusted by a factor of 1.10 to account for profit since other factors related to system assembly do not apply. These adjusted cost data were used to develop the cost estimating relationships shown in Figure 4.2 for the four major components of the alighting gear -- structure, controls, wheels ar es, and tires.

Only in the case of the alighting gear structure did there appear to be a reduction in cost per pound with increased weight. An 85 percent slope, which was discussed in Section 4A, was consistent with the data for alighting gear structures of less than 10,000 pounds (i.e., small and medium size transports) and was used. For structure weights greater than 10,000 pounds (i.e., large transports), the data indicated that cost per pound leveled off with increased weight.

Table 4.2

ALIGHTING GEAR CONTROL SYSTEM COST

Major Component or Subassembly	Component Percent of Total Control Weight	Cost per Pound	Confidence Value
Anti-Skid	11%	$175-200	5
Actuators	19	175-200	6
Hydraulic Plumbing	24	5- 20	5
Fluid	8	0.68	8
Support, Attach, etc.	38	25- 75	3
Total Alighting Gear Controls*	100%	$ 63-93 (avg. $78/lb.)	5.0

*The total cost per pound is a weighted average based on the percent of total control weight. The total (overall) confidence value is a weighted average based on the percent of the total control cost. See Section 2C for further explanation.

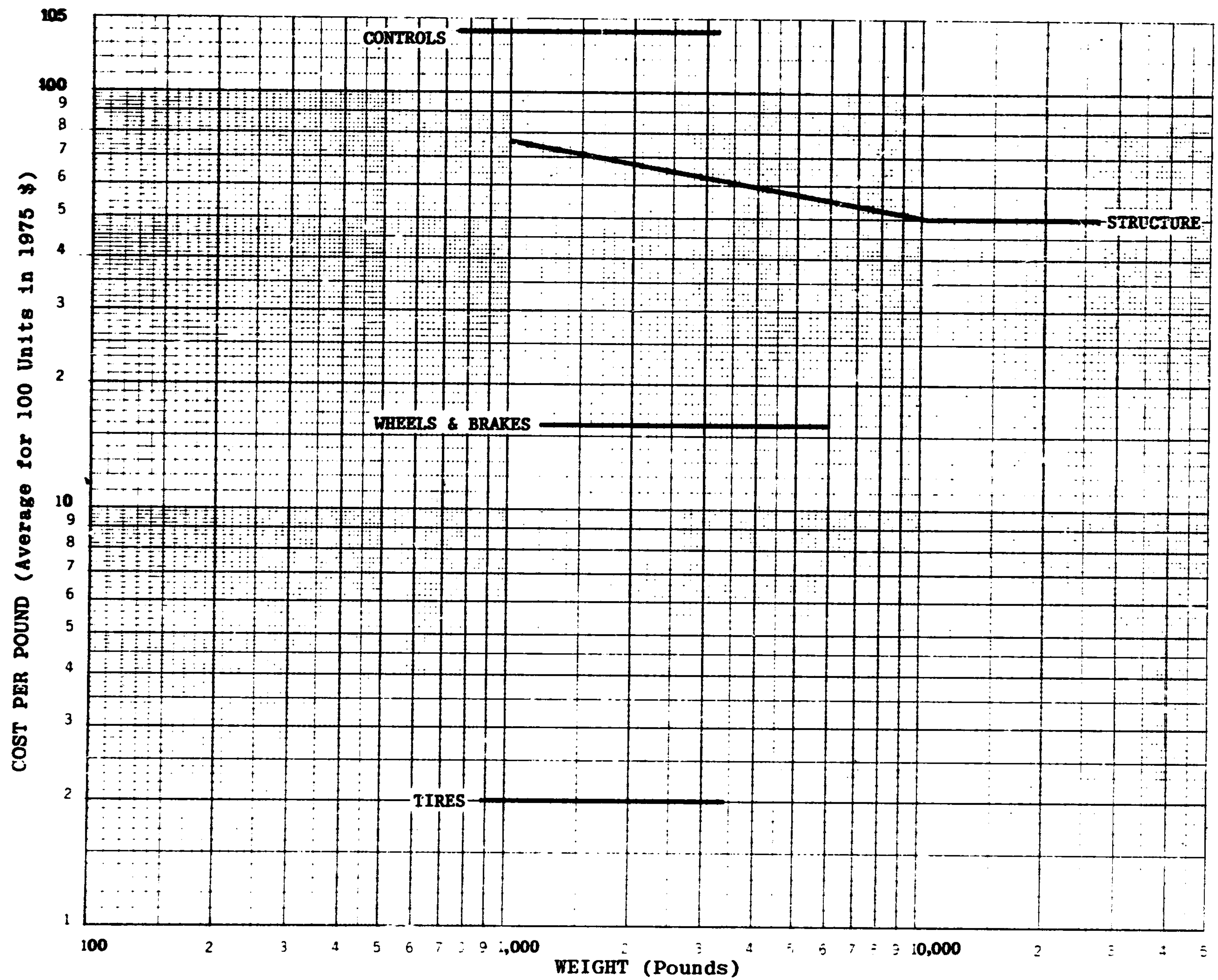


Figure 4.2 ALIGHTING GEAR SYSTEM CERs

Confidence values for the alighting gear structure, wheels and brakes, and tires of 8.0, 8.0, and 9.5, respectively, were assigned. The confidence value for the controls is 5.0 as shown in Table 4.2.

C. NACELLE SYSTEM

System Description

The nacelle system includes the cowl structure, the pylon structure and the sound suppression rings and supports. In general, the cowl represents the structure from the inlet to the engine rear face excluding the thrust reverser structure. The exhaust duct, aft cowling and thrust reverser structure aft of the engine rear face is included with the propulsion system. The fan thrust reverser including inner and outer ducting and core cowl over the length of the fan thrust reverser is also included with the propulsion system.

The pylon includes the apron, engine mounts and wing or fuselage attach fittings. Wing or fuselage attach bulkheads are included with their respective functional systems.

The sound suppression components include the rings and support struts. Any sound suppression treatment to the cowl inside walls is included with the cowl. Any inner skin and ducting for ice protection in the sound suppression rings and nacelle inlet lip are included with the anti-icing system.

System Cost

Subcontractor cost information was available for the C-5, C-141, KC-135 and C-130 from government data.[6] The same subcontractor produced the nacelles for all four aircraft. It should be noted that (except for the C-5) the subcontracted nacelle weight is about 30 percent greater than the total nacelle system weight. This additional weight includes engine accessories which were accounted for primarily in the propulsion system weight, but were a part of the subcontractor supplied nacelles. These engine accessories may include the starter and lubrication systems, fuel system tubing, hydraulic tubing, and anti-icing ducting. The specific engine accessories included vary for different contracts. When the nacelle costs included subcontractor supplied engine accessories, they were adjusted to remove the cost of those engine accessories by using the cost estimating relationships discussed in Section 4D. The C-5 was not considered further because it was abnormally expensive due to extensive use of titanium. The C-130 was also excluded because its nacelle is for a turboprop rather than pure jet engine. The C-141 and KC-135 cost per pound ranged from $88 to 105 per pound for weights of 2,500 to 5,600 pounds. These data were used to develop a cost estimating relationship for nacelles with no acoustic treatment and low bypass fan ratio engines.

Additional cost information was provided in a Douglas Aircraft Company report(11) which contained Allison Corporation data on quiet nacelles for high fan bypass ratio engines. These nacelle costs ranged from $154 to 115 per pound for weights of 5,000 to 10,000 pounds.

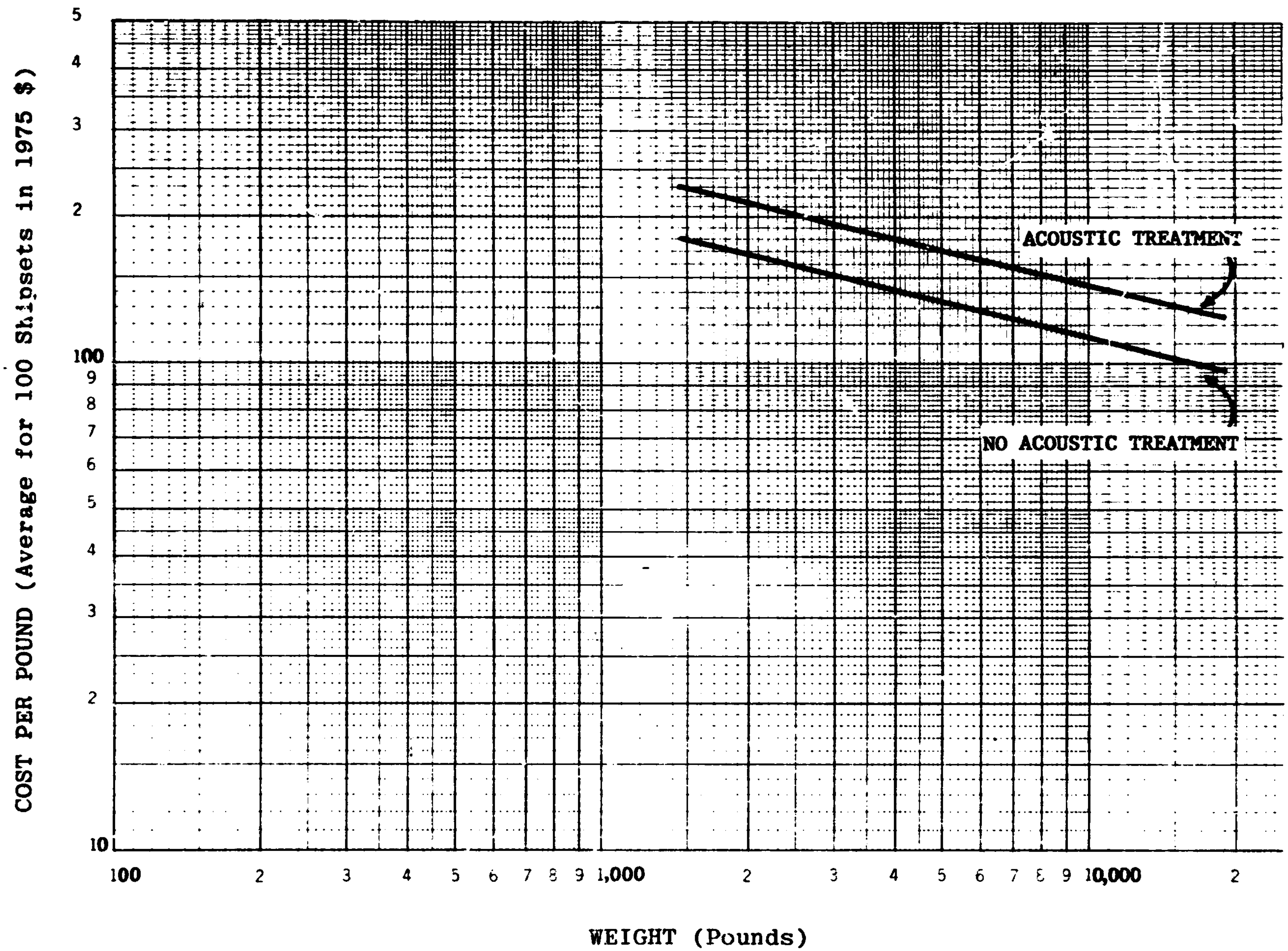
In order to determine a total system level cost, the subcontractor costs were adjusted by a factor of 1.21 as discussed in Section 2C. A factor was not included to account for assembly of engine components into the total nacelle system because the nacelle cost data already included "engine build-up."

The adjusted cost data were used to develop the two cost estimating relationships shown in Figure 4.3. An 85 percent slope for reduction in cost per pound with increased weight was assumed. This is the same slope used for the wing, tail and body structure. A confidence value of 6.0 was assigned for the nacelle.

Emerging Technologies

The use of composite materials in nacelles has been studied by Douglas Aircraft Corporation.(12) The substitution of advanced composites in the DC-10-30 nacelle (including thrust reverser) was estimated to save about 12 percent in weight and 12 percent in cost. Thus, the total cost would be reduced but the cost per pound would be unchanged.

Figure 4.3 NACELLE SYSTEM CERs



D. PROPULSION SYSTEM (LESS ENGINE)

System Description

The propulsion system includes the engines (which are not considered in this study), the fan exhaust thrust reverser system, the engine exhaust thrust reverser/spoiler system, the engine system and fuel system. The fan exhaust thrust reverser system includes the translating structure, cascades, blocker doors, fan exhaust ducting located with the translating structure, and the actuation system and controls. The engine exhaust thrust reverser/spoiler system includes all of the structure and systems located aft of the engine turbine exhaust flange which include the thrust reverser, tailpipe and bullet. The engine systems include components for cooling lubrication, ignition, throttle, and starting as well as the water injection system and cockpit controls. The fuel system includes the fuel fill and drain system, fuel distribution system, fuel vent plumbing, fuel dump system, integral wing tank sealant, and supplemental fuel tanks.

System Cost

Propulsion system cost information is conveniently grouped into the following categories: thrust reverser (including exhaust system), engine system and fuel system.

Subcontractor cost information was available for the C-5 and C-141 thrust reverser and exhaust system.(6) In addition, some approximate cost information was available for the DC-10 thrust reverser and exhaust system from a Douglas Aircraft Company study.(12) These costs ranged from $108 to 149 per pound for weights of 3,200 to 6,300 pounds and were significantly influenced by whether or not a fan type thrust reverser was used and whether or not acoustic treatment was used.

Engine system costs were estimated based on the breakout shown in Table 4.3. The percentages of the engine system weight are based on the DC-8, DC-10, C-141, and C-5 weight data. Although the component percentages vary considerably among the different aircraft, the error introduced into the total

Table 4.3

ENGINE SYSTEM COST

Major Component or Subassembly	Component Percent of Total Engine System Weight	Cost per Pound	Confidence Value
Starter	23%	$ 125-175	8.0
Start System Wiring & Ducts	16	25- 75	3.0
Throttle & Ignition Systems	32	60- 80	5.0
Cooling & Lube Systems	29	50-100	3.0
Total Engine System*	100%	$ 66-107 (avg. $87/lb.)	5.5

* Weighted average. See footnote to Table 4.2.

engine system cost is not more than $\pm$ 10 percent. The cost per pound values provided in Table 4.3 were estimated in the following manner. The starters for the C-130 and C-141 cost about $150 per pound. Miscellaneous wiring and ducts were estimated to cost $25 and 75 per pound as discussed in Section 4H. Most of the weight in the throttle and ignition systems is in the mechanical cockpit throttle controls and linkages to the engines. The cost of $60 to 80 per pound for mechanical controls which is discussed in Section 4E was, therefore, used. The engine cooling and lube systems include ducts, plumbing, valves and other mechanical components which were very approximately estimated to cost between $50 and 100 per pound based on similar types of components which are discussed later for other aircraft systems. The average cost per pound for the engine systems is $87 as shown in Table 4.3.

Fuel system costs were estimated based on the breakout shown in Table 4.4. The percentages of the fuel system weight are based on DC-8, L-1011, C-141 and C-5 data. The cost per pound estimates are based on similar types of components used in the hydraulic system as discussed in Section 4F. The average cost per pound for the fuel system is $31.

In order to arrive at a total propulsion system cost, the thrust reverser and engine system costs were adjusted by an approximate factor of 1.21 as discussed in Section 2C. A factor to account for assembly of components into the total propulsion system was unnecessary because the nacelle system cost estimating relationships account for "engine build-up" including the thrust reverser and engine system integration with the nacelle. However, the fuel system cost was adjusted by a factor of 1.33 because most of the components are located outside the nacelle and require extensive integration.

The cost estimating relationships are shown in Figure 4.4. The three separate cost estimating relationships for the thrust reverser represent different types of thrust reversers. An 85 percent slope for reduction in cost per pound was assumed based on the slope used for the nacelle.

Table 4.4

FUEL SYSTEM COST

Major Component or Subassembly	Component Percent of Total Fuel System Weight	Cost per Pound	Confidence Value
Pumps	5%	$ 75-150	6.0
Wiring	4	25- 75	3.0
Tubing, Fittings & Valves	64	20- 50	4.0
Sealant	27	1	3.0
Total Fuel System*	100%	$ 18- 43 (avg. $31/lb.)	4.1

* Weighted average. See footnote to Table 4.2.

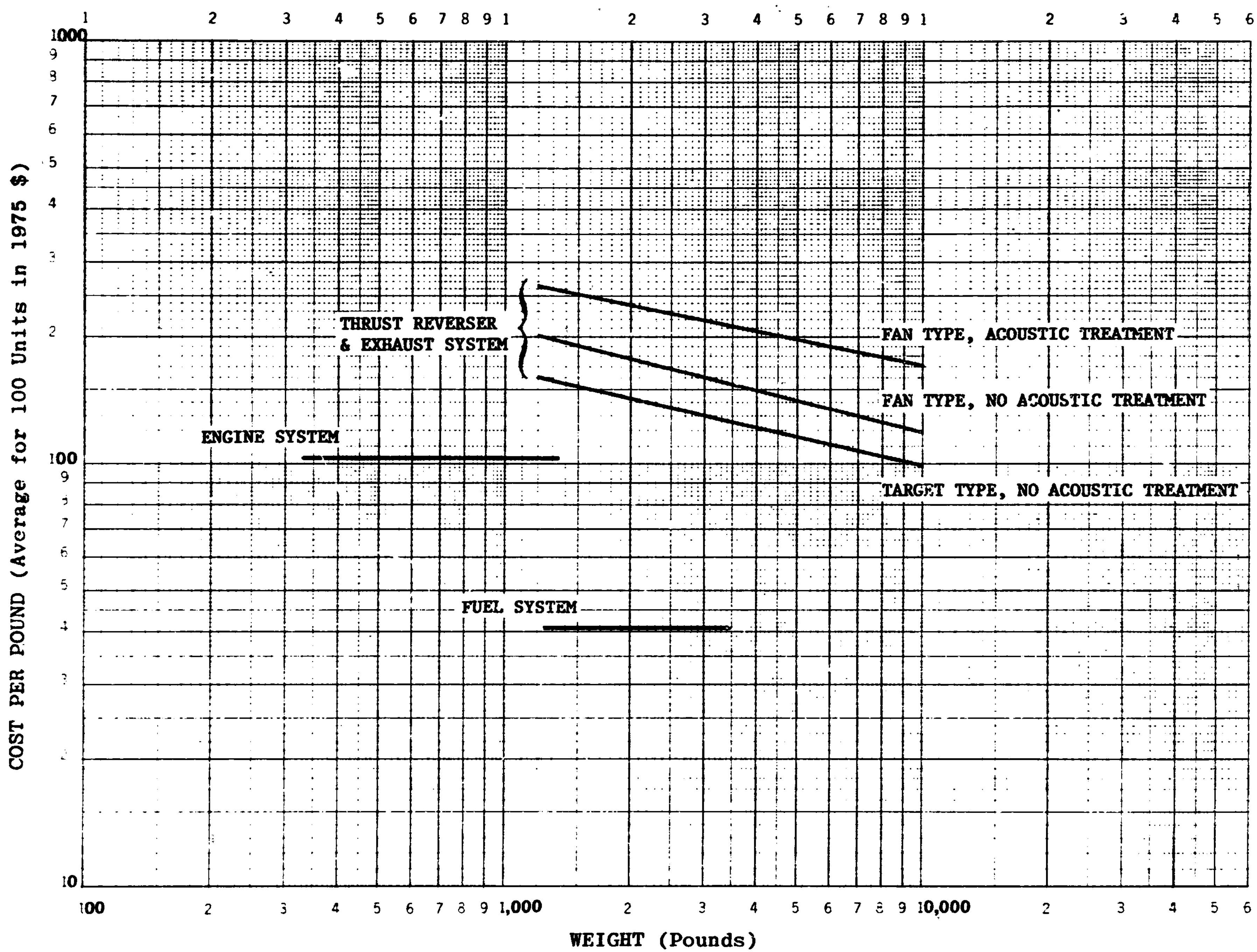


Figure 4.4 PROPULSION SYSTEM CERs

A confidence value of 6.0 was assigned for the thrust reverser. Confidence values for the engine system and fuel system were estimated at 5.5, and 4.1, respectively, as shown in Tables 4.3 and 4.4.

E. FLIGHT CONTROLS SYSTEM

System Description

The flight controls system includes the following components: cockpit controls, mechanical controls, hydraulic controls (actuators, control valves, plumbing and fluid), control surface dampers, electrical controls (except the integrated flight guidance and controls), and miscellaneous supports, fairleads, rub strips, and attachments. Military Standard 1374 also includes the autopilot in the flight control system. But, in some of the recent transport aircraft, it is difficult to separate the autopilot system from the flight guidance and control system because of the interdependency among components. Therefore, in this study the autopilot system is included with the integrated flight guidance and control system which is part of the avionics system.

Flight control functions may be broken into two groups: those performed by the primary flight controls and those performed by the secondary flight controls. Primary flight controls consist essentially of controls for the horizontal stabilizer, rudder, ailerons and spoilers. These provide pitch, roll and yaw control about all three axes. The secondary flight control system provides for symmetrical operation of wing leading edge slats and trailing edge flaps. This action provides lift augmentation for aircraft takeoff and landing.

Flight controls are typically powered by one or a combination of three sources; the hydraulic system, the pneumatic system or by separate motor servos. Other types of power are used occasionally, including electricity (electromechanical controls) and the use of fuel as the hydraulic medium when it is already at the required pressure (fueldraulic controls). The type of flight controls that are used for a particular application depends largely on the type of power that is most readily available. Although any type of control can accomplish any given function, each offers certain unique characteristics. For example, mechanical flight controls are lighter and less expensive and offer automatic synchronization. Because they require relatively little space and are attached to the control surface at several points, mechanical flight controls permit a thiner and lighter structure. Pneumatic flight controls require a larger volume within the structure because of the large duct sizes of the distribution system.

Actuators are the key components in the flight controls system from both a cost and functional standpoint. They provide the link between the pilot's controls and the aerodynamic surfaces that must move to control the flight of the aircraft. The term actuator as used in this report includes associated components such as control values in the case of hydraulic actuators (also known as servo mechanisms or servo actuators) and gears and motors in the case of mechanical actuators.

System Cost

The following categories of major components and subassemblies are used in this study for the flight controls system: hydraulic actuators, mechanical actuators, mechanical controls, electrical controls, cockpit controls, plumbing, fluid , supports and miscellaneous. Detailed cost information has been aggregated into these categories to develop cost estimating relationship for the flight controls system.

Cost information for some flight control actuators for two recent aircraft is shown in Table 4.5. The cost of subcontractor supplied flight control actuators varies from about $70 to 200 per pound on the 747. However, when 747 actuators are grouped by power source, a much narrower range of about $175 to 200 per pound is indicated for hydraulic actuators, a cost of $122 per pound is indicated for the pneumatic actuators and a cost of about $70 per pound is indicated for actuators which are primarily mechanical. The high cost of $400 per pound for L-1011 leading edge actuation is the result of the new, lightweight technology that enabled total leading edge flight control system weight to be reduced significantly. Its 648 pounds compares to 1,184 pounds for 747 and 1,274 pounds for DC-10-10 leading edge actuation.

Table 4.5

COSTS AND WEIGHTS OF RECENT FLIGHT CONTROL ACTUATORS

Actuator Type	Cost	Weight (lb)	Cost per Pound
747			
Aileron (hydraulic actuators and control valves)	$ 46,000	263	$175
Elevator (hydraulic actuators and control valves)	95,000	483	197
Rudder (hydraulic actuators and control valves)	33,000	186	177
Leading Edge (drive shaft, rotary actuator, ball screw actuator and transmission, pneumatic drive unit)	126,000	1,029	122
Trailing Edge (drive shaft, gearbox, transmission, brakes, drive motor, ball screw actuators, hydraulic control valves)	100,000	1,478	68
Spoiler Speed Brake (hydraulic actuators and control valves)	61,000	312	196
Horizontal Stabilizer (actuator assembly, motor, gearbox, brakes, hydraulic controls)	37,000	516	72
L-1011			
Leading Edge (hydromechanical actuator, control valve)	100,000	249	402

Mechanical controls are the shafting and linkages that connect the actuators with the movable surfaces. It was assumed that the cost of these would be similar to that of mechanical actuators indicated on Table 4.5 (about $70 per pound) as they are made of expensive metals and machined to close tolerances.

The electrical controls monitor the positions and operations of the flight controls and signal the flight crew regarding any malfunctions. Their cost is assumed to be $560 per pound as they are similar to the cost of instruments and avionics which is discussed in Section 4J.

Cockpit controls include items such as control column levers, wheels, and peddles for the flight crew. A cost of $40 to 60 per pound was assumed to be appropriate for this type of equipment. Although no specific data were available, these were believed to be less complex and, therefore, less expensive than mechanical actuators which were estimated to cost about $70 per pound. Further, this equipment comprises only about four percent of the total flight control system weight and the overall cost estimating relationship is, therefore, only very slightly influenced by this component.

The plumbing, hydraulic fluid and supports and miscellaneous equipment costs are based on data presented in Section 4F.

The cost information for each major component or subassembly discussed above is summarized in Table 4.6 together with its percentage of system weight and confidence value. The system weight percentages are averages for five aircraft (DC-9-30, DC-10-10, L-1011, 747 and C-141A). Since the weight percentages did not vary discernably by size or type of aircraft, separate calculations were not made for small, medium and wide body commercial aircraft and military transport aircraft. The average cost per pound for the total flight control system is $102. The relatively low overall confidence (6.2) associated with the total flight control system cost is due largely to the fact that, while excellent data were collected on actuators and hydraulic fluid, adequate data were not available for most of the other components.

Table 4.6

FLIGHT CONTROLS SYSTEM COST

Major Component or Subassembly	Component Percent of Total System Weight	Cost per Pound	Confidence Value
Hydraulic Actuators	16%	$175-200	9.5
Mechanical Actuators	25	70	7.5
Mechanical Controls	29	70	5
Electrical Controls	4	560	4
Cockpit Controls	4	40- 60	2
Plumbing	6	5- 20	5
Fluid	3	0.68	8
Supports and Miscellaneous	13	25- 75	3
Total Flight Controls System*	100%	$ 91-113 (avg. $102/lb)	6.9

*Weighted average. See footnote to Table 4.2.

The cost information presented in Table 4.6 represents subcontractor costs only. In order to determine a total system level cost, this cost was adjusted by an approximate factor of 1.33 as discussed in Section 2C. The adjusted cost data were used to develop the cost estimating relationship shown in Figure 4.5.

Emerging Technologies

Power-by-wire is an application of fly-by-wire technology to the flight controls system which could significantly change both the design and cost of future flight control systems. In power by wire, a discrete electronic signal is transmitted by wire to servo pumps and reservoirs which are colocated with the hydraulic actuators at the surface to be actuated. This design was initiated for fighter aircraft because wire may be made redundant more easily than plumbing and, therefore, offers greater survivability. A major problem associated with power-by-wire is that it concentrates greater loads at the surface actuators and, thereby, adversely effecting structural design. To accomplish power-by-wire, an improved electrical distribution system which includes remote load control and multiplexing would be required. The implication of this concept for the electrical system is discussed in more depth in Section 4G. The Air Force has funded two power-by-wire study efforts. However, no applications of power-by-wire are contemplated in the near future.

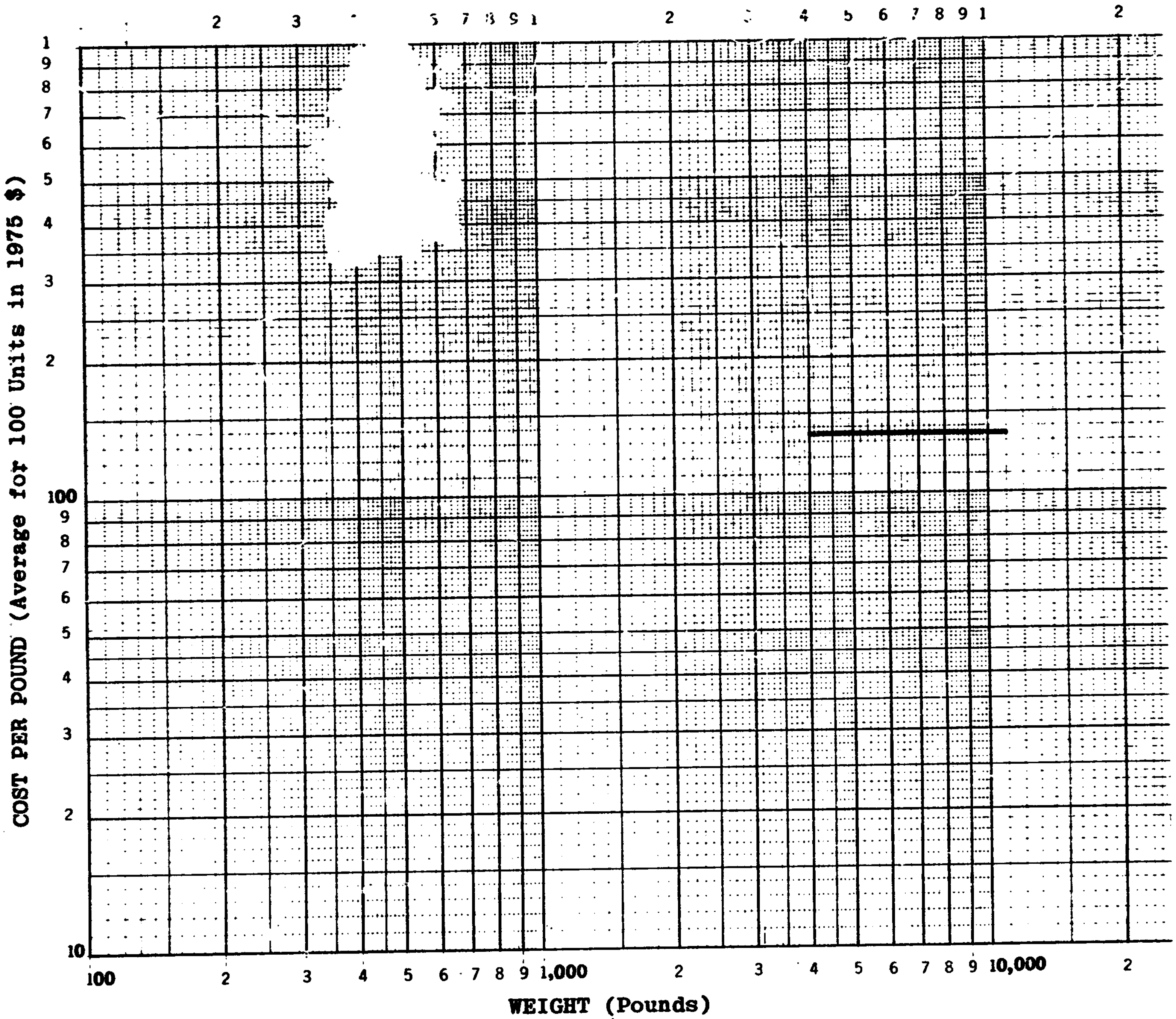


Figure 4.5 FLIGHT CONTROL SYSTEM CER

F. HYDRAULIC SYSTEM

System Description

The hydraulic system provides power to operate the alighting gears and the hydraulic flight control components. This system is required to meet peak system demands during the most critical flight and landing conditions. Because of the criticality of its function, it is generally redundant. For example, the L-1011 has four separate, parallel, continuously operating hydraulic systems such that it can complete its flight plan with two inoperative systems and can maintain control and land safely with three inoperative systems.

Engine driven hydraulic pumps are the primary power source for hydraulic systems. These are occasionally supplemented by a pump connected to an air turbine motor for emergency or peak power requirements. Electric motor-driven pumps powered by the auxiliary power unit provide power for low flow ground checkout and preflight pressurization. Power transfer units are one-way motor-driven pumps which provide the capability of generating fluid pressure in one system through pumps driven by hydraulic motors powered by another source. In addition to pumps, the hydraulic system includes reservoirs, accumulators, filters, valves, controls and plumbing.

The hydraulic system has remained technologically stable over the last several years as hydraulic operating pressures for transport aircraft have stayed the same. This has resulted in the frequent use of standard, off-the-shelf components. Recent military fighters and bombers have used higher pressure systems which imply weight advantages but appear to be less reliable. One reason that transport aircraft hydraulic systems have remained tehnologically stable is that commercial interests are unwilling to pay for designing, developing and testing new hydraulic system components such as pumps. Thus, military aircraft hydraulic systems seem to be more technologically advanced because the government has underwritten this research.

System Cost

The following categories of major components and subassemblies have been used in this study for the hydraulic system: hydraulic pumps; reservoirs and accumulators; filters, regulators, valves and manifolds; plumbing and supports; hydraulic fluid; and miscellaneous material. The detailed cost information has been aggregated into these categories to develop the cost estimating relationship for the hydraulic system.

Some recent costs of representative hydraulic system components are provided in Table 4.7. Hydraulic pumps vary in cost between $1,200 and 2,500 and their unit weights vary between about 19 and 36 pounds. Thus, a cost of $65 to 75 per pound is indicated. The cost of hydraulic pumps has become a significant concern to aircraft manufacturers. In fact, some procurement contracts for hydraulic pumps have recently been awarded to low bidders even though their product was heavier than that of their higher priced competition. Previously, contracts were almost always awarded to the bidder with the lightest weight pump.

Based on limited information, reservoirs and accumulators cost between $19 and 23 per pound.

There was no cost information available for filters, regulators, valves, and manifolds. They were assumed to have an average cost about midway between the cost of pumps and the cost of reservoirs and accumulators. Thus, by averaging the lower and upper bounds of the costs for those items, a cost of $40 to 50 per pound was obtained.

An approximate cost of $5 per pound for hydraulic plumbing and supports was indicated by a parts supplier. However, use of stainless steel would increase this cost by three to fourfold. Thus, a cost between $5 and 20 per pound was used.

Hydraulic fluid costs about $300 for a 55 gallon barrel. This is $5.45 per gallon or, based on a weight of 8 pounds per gallon, $0.68 per pound.

Table 4.7

REPRESENTATIVE COSTS OF HYDRAULIC SYSTEM COMPONENTS

Item Description	Approximate Unit Price	Comments
Engine-Driven Hydraulic Pump (15HP)	$1,200-1,500	For small aircraft such as F-5.
Engine-Driven Hydraulic Pump (45HP)	1,800-2,500	For most transport aircraft. Typical cost is about $2,000.
Reservoirs	500-1,000	
Accumulators	200	
Plumbing (per pound)	5-20	High cost is for stainless steel.
Fluid (55 gallon drum)	300	

Miscellaneous material (including controls, wiring, and switches) was assumed to cost from $25 to 75 per pound. This cost range is used in several places in this report for miscellaneous items such as wiring, ducting and brackets. The basis for the cost range is some data on wiring and pneumatic ducting which indicates a cost per pound of about $50. Because this cost is uncertain and may not be representative of the cost of other miscellaneous items, a cost range of plus or minus fifty percent was used.

The cost information for each major component or subassembly discussed above is summarized in Table 4.8 together with its percentage of system weight and confidence value. Based on an analysis of hydraulic system component weights for the DC-9, DC-10, L-1011, 747 and C-141A, it was determined that they varied only slightly as a percent of the system weight. The average cost per pound for the total hydraulic system is $27 which represents subcontractor costs only. In order to determine a total system level cost, the $27 per pound was adjusted by an approximate factor of 1.33 as discussed in Section 2C. The adjusted data were used to develop the cost estimating relationship shown in Figure 4.6.

Installation for the hydraulic system is believed to be very expensive given the many feet of plumbing required and may be analogous to the conventional plumber's bill which typically includes a relatively small amount for materials and a large amount for labor. As noted in Section 2C, however, the assembly and installation factor used is believed appropriate for the entire aircraft and has not been adjusted by aircraft system. It is expected, however, that installation for the hydraulic system would be significantly greater than the average. A confidence value of 6.3 was calculated for the hydraulic system CER.

Table 4.8

HYDRAULIC SYSTEM COST

Major Component or Subassembly	Component Percent of Total System Weight	Cost per Pound	Confidence Value
Hydraulic Pumps	17%	$65-75	9
Reservoirs and Accumulators	8	19-23	7
Filters, Regulators, Valves, and Manifolds	5	40-50	3
Plumbing and Supports	36	5-20	5
Hydraulic Fluid	22	0.68	8
Miscellaneous Material*	12	25-75	3
Total Hydraulic System**	100%	$20-33 (avg. $27/lb)	6.3

* Includes controls, wiring, and switches.

**Weighted Average. See footnote to Table 4.2.

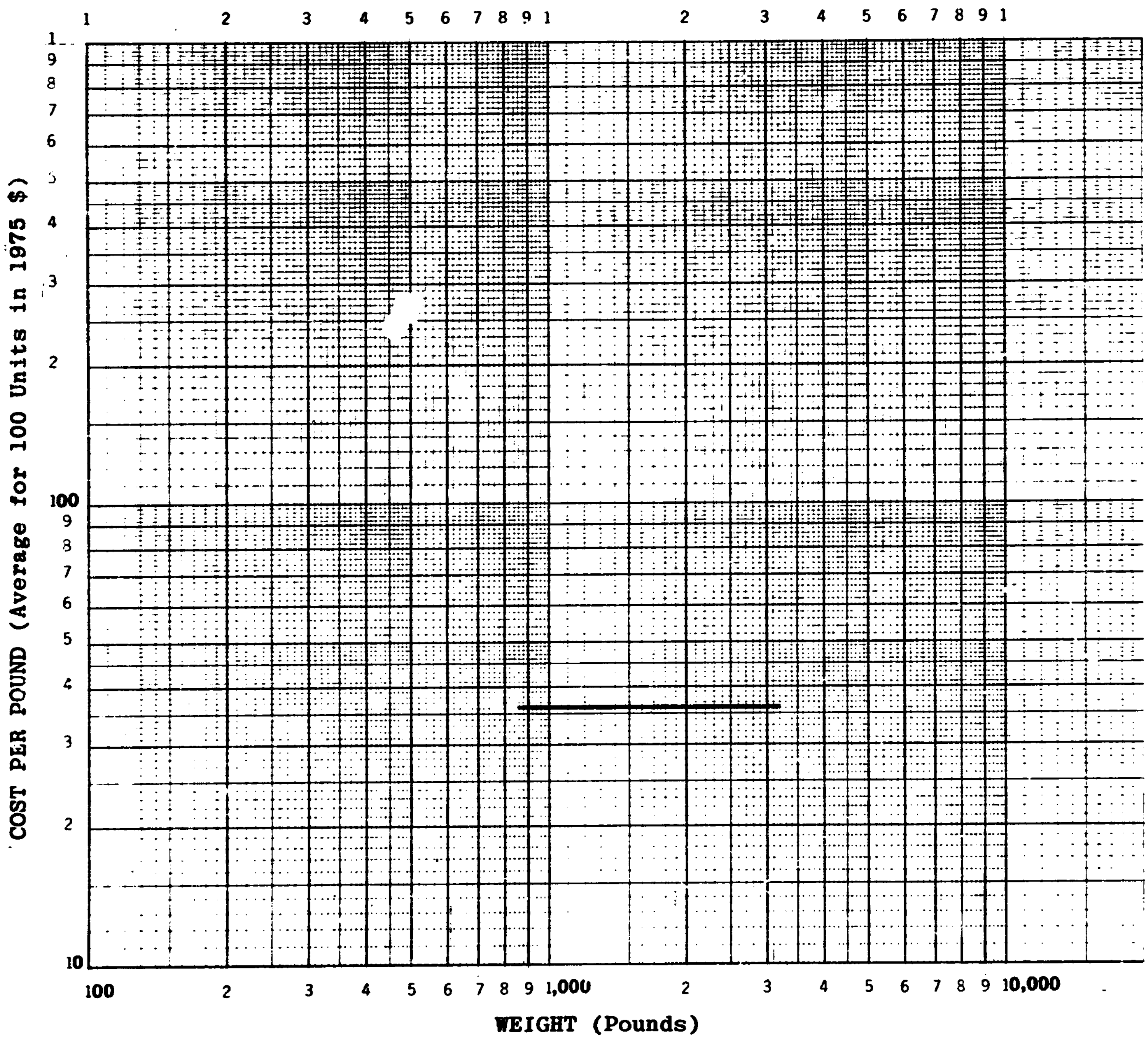


Figure 4.6 HYDRAULIC SYSTEM CER

G. ELECTRICAL SYSTEM

System Description

The electrical system supplies power to a variety of operating components on an aircraft including, among others: lights, avionics, instruments, passenger and cargo doors, galleys, environmental control system, fire extinguishers, landing gear controls and auxilliary power unit (APU) starting.

The electrical system consists of the AC power system, DC power system and lighting system. The AC and DC power systems include power generating equipment (i.e., constant speed drives, generators and batteries) and the necessary controls, wiring, cables, fittings and supports to distribute the electrical power from the power source to the electrical power center. The AC and DC power systems also include the structure and circuitry of the electrical power center. Circuitry from the power center to the various components using electricity are included with their respective functions.

The lighting system includes all interior and exterior lights with their supports and associated circuitry. For commercial aircraft, the interior lighting system includes the individual passenger reading lights.

The constant speed drive (CSD) provides the crucial link between the engine gearbox and the generator as it converts variable engine speeds to a constant output speed so as to drive the generator at a constant frequency. The original CSD, a hydraulic differential CSD introduced in the 1940's, had very limited endurance (a maximum of about 1,000 flying hours before overhaul) and was, therefore, not practical for commercial use. The axial gear differential (AGD) CSD was developed to provide greater reliability, longer life, lower operating costs and lighter weight. The AGD has now been applied to virtually all transport aircraft. The newest CSD development to be installed on a transport is the integrated drive generator (IDG) which is used on the L-1011 as well as several fighters and bombers. It combines an AGD with an advanced design spray oil cooled generator in a common housing and thereby reduces the combined weight by about 35 to 40 percent.

The generator converts mechanical energy from the engine gearbox and CSD to electrical energy. Like CSDs, many technological advances have been incorporated into generators. They have evolved from air cooled, to oil cooled, to spray oil cooled. Current spray oil cooled generators weigh about half as much as the lightest generators available in 1965 and reliability has been increased by as much as a factor of ten. As noted above, spray oil cooled generators are an integral part of the new IDGs.

A generator control unit is required for each generator to operate independently. It contains the generator voltage regulator, protection circuits and logic circuits. In normal parallel operation the load is shared by all generators. If one or more generators fails, all AC buses are supplied by the remaining generators to the limit of their capacity. The buses then collect and distribute electric power. A bus protection panel includes control and protection when external power sources are used so that aircraft systems cannot be subjected to improper frequency or phasing voltage. Current transformers are used both individually and collectively to sense system currents. The electrical load control unit is similar to a circuit breaker in function as it automatically interrupts electric current under an abnormal condition and protects distribution wire. Transformer rectifiers supply power to a DC bus and are the key components in changing AC supply into controlled DC output. The static inverter and the battery furnish flight critical AC and DC power for instruments, navigation and selected lighting when power is not available from other sources. The battery functions to start the APU as well as providing standby and emergency power. Battery charge is maintained by a charger energized by the AC system.

Aircraft lighting is provided in four general areas: exterior, crew station, cabin and cargo compartment. Exterior lighting requirements are defined by the cognizant government agency/specification: the FAA for commercial aircraft and Military Specification 6503H for military aircraft. Because specifications are changed with relative frequency, exterior lighting retrofits are common. Aircraft performance and a profile have a major impact on cost of many exterior lights. For example, four lights may be required to do the work of one or two when aircraft performance requirements severely limit the potential location and protrusion of lights necessary to meet functional requirements. This problem does not usually exist for large, subsonic transport aircraft. Like exterior lights, the design and cost of crew station and interior cargo compartment lights are also dictated primarily by the function they must perform.

The design and, thereby, the cost of passenger cabin lighting is driven largely by aesthetic considerations rather than by function alone. Since there is no clear right or wrong way to illuminate a cabin, the cost for lighting comparable aircraft can vary by as much as 30 to 40 percent.

System Costs

The following categories of major components and subassemblies have been used in this study for the electrical system: AC power generation; AC power conversion; AC power distribution; DC power; interior and exterior lights. Detail cost information has been aggregated into these categories to develop the cost estimating relationships for the electrical systems.

AC power generation equipment represents a significant expense as one set per engine is required and an additional set is occasionally fitted to the APU. Approximate cost information for recent AC power generation equipment is provided in Table 4.9. The CSD unit cost indicated is felt to be typical, although it can vary from $15,000 to 30,000 for transport aircraft. CSDs employ off-the-shelf technology to the extent possible. This is illustrated by the fact that CSDs attached to JT8D engines (on the DC-8, DC-9, 727 and 737, for example) are about 95 percent common. There are no significant differences between CSDs installed on military transports and those on commercial aircraft.

The cost of generators has increased from about $1,200 to 1,400 in 1955 to about $3,000 to 3,500 today. This price increase is about equal to the inflation rate, however, manufacturing and design technology improvements have actually offset inflation to such a large extent that more than half

Table 4.9

REPRESENTATIVE COSTS FOR

TRANSPORT AIRCRAFT ELECTRICAL SYSTEM COMPONENTS

Description	Approximate Quantity Required	Unit Cost	Total Cost*
AC Power Generation			
AGD Constant Speed Drive	1 per engine	$ 24,000	$ 96,000
Generator	1 per CSD	3,000-3,500	12,000- 14,000
Quick Attach Detach Kit (QAD) and Plumbing	1 per CSD	500- 700	2,000- 2,800
Heat Exchanger to Cool CSD Oil	1 per CSD	300- 500	1,200- 2,000
AC Power Conversion			
Static Inverter	2 or 3 per aircraft	3,000-4,500	6,000- 13,500
AC Power Distribution			
Generator Control Box	1 per generator	2,000-3,000	8,000- 12,000
Contactor**	2-4 per channel	500	4,000- 8,000
Bus Protection Panel	1 per aircraft	1,200	1,200
Relays and Circuit Breakers	1,000 per aircraft	50-300	75,000-200,000
Current Transformer**	5 per channel***	75 for single 150-400 for package	1,500- 5,000
Electrical Load Control Unit**	1 per CSD	800-1,200	3,200- 4,800
Wiring-Installed	(600-1,200 pounds)	--	30,000- 50,000
DC Power System			
Battery	2 per aircraft	1,000	2,000
Transformer/Rectifier	1 per channel	750	3,000
Total Cost*			$241,900-409,300

* Assumes four channels per aircraft. Does not include lighting - see Table 4.10.
** Current transformers and load controllers may be used interchangably. If a load controller is used, only two contactors are required per channel.
***In addition to 3 included in generator and part of generator cost.

of the price increase may be attributed to the greater use of more expensive, lightweight materials.

The cost of AC power generation equipment averages $28,600 per engine. The weight ranges from 165 to 205 pounds. Therefore, a cost of $151 to 188 per pound was estimated. This applies to AGD type systems. AC power generating equipment employing the new IDG costs roughly 20 percent more.

AC power conversion equipment consists of several static inverters which cost about $3,800 each as indicated in Table 4.9. Their unit weight is about 15 pounds, therefore, a cost of about $250 per pound is estimated.

AC distribution equipment are a diverse collection of items that include generator control boxes and panels; voltage regulators, contactors, bus panels; circuit breakers, relays and switches; distribution boxes and panels; and miscellaneous wire, conduit and supports. Of those items listed above, the quantity, and hence weight, of circuit breakers and switches and the miscellaneous wire, conduit and supports, vary greatly with the size of the aircraft - from 500 to 2,500 pounds. The balance of the items remain relatively fixed varying from about 190 to 250 pounds for a wide range of aircraft sizes. By using the information contained in Table 4.9 and correlating it with detailed weight statements, it was determined that these items cost on the order of $80 to 100 per pound.

The DC power system includes batteries, chargers, transformer rectifiers, circuit breakers, relays, limiters, distribution boxes and panels, and miscellaneous wire and conduit. By using the information contained in Table 4.9 and correlating it with datailed weight data, a range of $50 to 58 per pound was determined for the DC power system.

Lighting system costs are shown in Table 4.10 for a variety of aircraft types. These costs are for the light and fixtures but not for controls or power supplies unless otherwise noted. Lights and fixtures comprise from 60 to 85 percent of the total interior lighting weight and 40 to 60 percent of the total exterior lighting weight. The remainder of the weight includes transformers, wire supports, plugs, etc. By correlating the cost

Table 4.10

REPRESENTATIVE QUANTITIES AND COSTS
FOR TRANSPORT AIRCRAFT LIGHTING

	General Aviation				Commercial Aviation				Military		
	Single Engine		Multi-Engine		Commuter		Transport		Transport		
Exterior Lights	Qty	Cost	Qty	Cost	Qty	Cost	Qty	Cost	Qty	Cost	Remarks
Anti-Collision (red)	(2)	$100	(2)	$100	(2)	$150	(2)	$350	(2)	$350	Many aircraft now use both red and white systems; some use only red. White is based on high-intensity strobes.
Anti-Collision (white)	(2)	125	(3)	125	(3)	125	(3)	450	(2)	750	
Fuselage									(2)	30	
Scanning (inc. lens)	(2)	400	(2)	400	(2)	400	(2)	400	(2)	400	
Landing (fixed)	(1)	30	(2)	50	(2)	50	(2)	150	(2)	150	An airplane will have fixed landing lights with lens fairing or retractable landing lights, not both.
(plus lens fairing)			(2)	50	(2)	50	(2)	200	(2)	200	
Landing (retractable)			(2)	200	(2)	300	(2)	600	(2)	600	
Taxi	(1)	30	(1)	30	(1)	30	(2)	150	(2)	150	
Position Forward	(2)	15	(2)	30	(2)	30	(2)	50	(2)	50	
(plus lens fairing)			(2)	50	(2)	50	(2)	100	(2)	100	
Position aft (inc. lens)	(1)	15	(1)	15	(1)	15	(2)	100	(2)	100	It is common for large aircraft to install aft position lights in trailing edge of wing tips. Includes power supplies and batteries.
Emergency Exterior Lights					(2)	200	(5-9)	400			
Logo (advertising)					(2)	10[illegible]	(3)	400			
Cargo Handling							([illegible])	400	(3)	40	
Equipment Bay	([illegible])	10	(2)	10	(2-5)	10	([illegible]10)	200	(2-10)	20	Based [illegible] incandescent—for fluorescent X3.
Formation	—	—	—	—	—	—	—	—	(9-12)	30	Based on electroluminescent strips—for incandescent X2. Not commonly used.
Subtotal Exterior Lights	$1,365-1,385		$2,200-2,240		$3,100-3,230		$[illegible]-[illegible]7,150		$12,190-13,200		

Table 4.10 (Cont'd.)

REPRESENTATIVE QUANTITIES AND COSTS
FOR TRANSPORT AIRCRAFT LIGHTING

	General Aviation				Commercial Aviation				Military		
	Single Engine		Multi-Engine		Commutor		Transport		Transport		
	Qty	Cost	Qty	Cost	Qty	Cost	Qty	Cost	Qty	Cost	Remarks
Crew Station Lights											
General Illumination	(1)	$15	(1)	$15	(1-2)	$25	(1-2)	$25	(1-2)	$25	Based on incandescent—for fluores. X3.
Panel Flood	(2-5)	5	(2-5)	5	(2-6)	5	(2-6)	30	(2-6)	30	
Map Reading	(1)	15	(1-2)	15	(1-2)	15	(2-4)	25	(2-4)	25	Generally one per crew member.
Glare Shield	(1)	15	(1)	30	(1)	30	(1)	30	(1)	50	Based on incandescent—for fluores. X3.
Center Console Flood							(1)	75	(1)	75	
Thunderstorm									(4-5)	25	
Subtotal Crew Station Lights	$55-130		$70-190		$80-300		$260-655		$360-780		
Cargo Compartment											
Ceiling Lights							30/ft		30/ft		Figure two or three rows in wide-body aircraft.
Subtotal Cargo Comp. Lights	0		0		0		$850-7,000		$1,200-10,900		
Cabin Lights											
Ceiling-Incandescent					$		$ 50/unit		$		Quantity depends on decor.
Ceiling-Fluorescent					20/ft		30/ft				Figure two rows, possibly four through cabin of wide-body aircraft.
Window-Fluorescent							80/window		15/ft		
Reading					20/seat		20/seat				
Aisle							2/ft		20/seat		Figure two rows for wide-body aircraft
Emergency-Aisle					5/ft		5/ft				includes power supplies and batteries.
Emergency-Signs					100/exit		100/exit		100/exit		Figure two rows for wide-body aircraft.
Passenger Signs					10/row		10/row				Figure X2 for wide-body aircraft.
Stewardess Call Indicators							5/seat group				
Lavatory							300/lavatory				
Service Centers							200/center				
Galley							30/ft				
Subtotal Cabin Lights	0		0		$650-1,900		$4,600-40,000		$3,000		
Total Aircraft Lights	$1,420-1,515		$2,270-2,430		$3,830-5,430		$15,660-65,000		$16,750-27,800		
Caution and Warning Lights	(5-10)	$10	(10-20)	$20	(20-50)	$20	(100-600)	$30	(50-200)	$30	Costs include drivers and indicators except for general aviation. Provided for information only - part of avionics system.

data in Table 4.9 with detailed weight statements and using a factor of $50 per pound to represent miscellaneous material as discussed in Section 4F, a cost of $45 to 80 per pound was determined for both exterior and interior lighting. Although caution and warning indicators are part of the avionics system, they are often provided by the lighting subcontractor and their cost is shown on Table 4.10 for information only.

The above cost information is summarized in Table 4.11 together with percentages of system weight and confidence values for the four classes of aircraft defined in Section 2C. As might be expected, the weight of the electrical system as a percentage of MEW decreases as the aircraft get larger. However, there is a notable lack of consistency regarding the relative mix of electrical system components among the classes of aircraft. While there is no apparent reason for many of the variations in the mix, some can be explained by close examination. For example, the large decrease in AC power generation equipment weight between medium and wide-body aircraft is because most medium aircraft considered have four engines while two of the three wide body aircraft have only three engines.

Table 4.12 provides electrical system cost information for each of the four classes of aircraft. This was accomplished by applying the methodology described in Section 2C. An average cost of $104 per pound is appropriate for small and medium commercial aircraft and for military aircraft. $89 per pound is appropriate for wide body aircraft. The difference in these costs is due to the variances in the mix of components included in the electrical systems of each of the various types of aircraft.

Table 4.12 also provides confidence values for the electrical system CERs. They range from about 7.9 to 8.3 depending on the aircraft type.

The costs presented in Table 4.12 represent subcontractor costs only. In order to determine total system level costs, these costs were adjusted by an approximate factor of 1.33 as discussed in Section 2C. The adjusted cost data were used to develop the cost estimating relationships shown in Figure 4.7.

Table 4.11

ELECTRICAL SYSTEM COST

Major Component or Subassembly	Component Percent of Total System Weight: Small	Medium	Wide Body	Military Transport	Cost per Pound*	Confidence Value*
AC Power	57%	85%	57%	78%		
Generation	27	22	11	24	$ 151-188	9
Conversion	1	2	1	2	250	9
Distribution	29	61	45	52	80-100	7
DC Power	19	2	6	10	50-58	7
Lights	24	13	37	12		
Interior	15	10	32	7	45-80	9
Exterior	9	3	5	5	45-80	9
Total Electrical System*	100%	100%	100%	100%	$ 76-118	8.0
Electrical System Percent of MEW	3.0%	2.8%	2.4%	1.6%		
Total Electrical System Weight (average pounds)	1,334	3,228	5,428	2,883		

* Weighted Average. See footnote to Table 4.2.

Table 4.12

ELECTRICAL SYSTEM

COST BY AIRCRAFT TYPE

	Small	Medium	Wide Body	Military Transport
CER	$88-113 (avg. $100/lb.)	$94-118 (avg. $106/lb.)	$76-102 (avg. $89/lb.)	$93-118 (avg. $106/lb.)
Confidence Value	8.3	7.9	7.9	8.0

Emerging Technologies

Technology related to the electrical system is rapidly advancing and many innovations should be implemented in the future. The potential application of new technologies to current methods of electrical power generation and distribution are discussed below.

Variable speed constant frequency (VSCF) technology is seen by some as eventually replacing the CSD. VSCF is actually a term which includes a variety of options for using solid state technology to convert the irregular input of the power source into a constant electrical output. Cycloconversion, DC link and high voltage DC are three such options.

Cycloconversion employs a cycloconverter which samples the irregular input from the generator at several selected points in order to provide a constant output. Since a cycloconverter can convert only to lower frequencies, a high speed generator is required to produce an input frequency of at least 1200 Hz that can be reduced to the desired constant 400 Hz output. This concept introduces a serious design problem since acceptable generator life cannot currently be achieved at the required speeds.

DC link converts variable frequencies into DC power and then converts DC to constant frequency AC with an inverter. Achieving reliability with DC link is a problem because it uses 2,000 to 4,000 solid state components and compatible joint operation is required. Further, the development of a lightweight inverter is required if DC link is to be feasible.

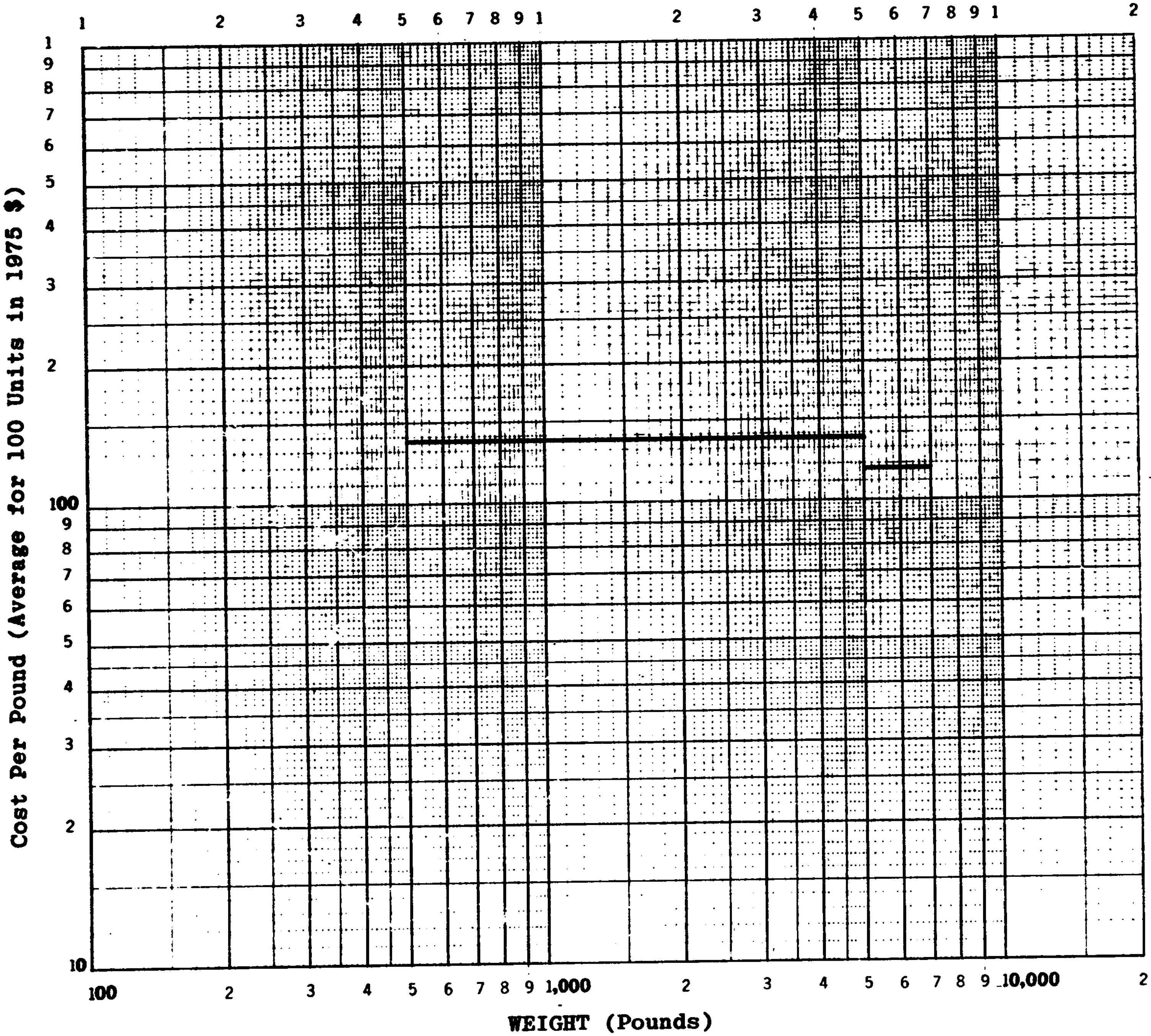


Figure 4.7 ELECTRICAL SYSTEM CERs

High voltage DC is theoretically a more efficient means of providing constant frequency output without a CSD than either cycloconversion or DC link and is presently being studied by the Navy. However, ultra high voltage circuit breakers must be developed for it to be achieved.

In comparing VSCF and CSD system costs, it must be noted that very different technologies (static vs. dynamic) are used. Since a CSD is a rotating apparatus, it has an inherent overload capability. Solid state VSCF components do not have an overload capability in excess of their stated maximum load. This requires extensive analysis to be performed regarding peak load requirements and design must be based on them. Research is currently being conducted to develop an instantaneous heat sink to achieve an overload capability and, thereby, avoid potential damage to electrical equipment.

The electrical distribution system is a major target of opportunity for technological advancement. In fact, it is felt that the electrical distribution technology employed in even the most recent transports (747, L-1011 and DC-10) is obsolete compared to an aircraft that would be designed today as it would undoubtedly employ more remote load control, signal multiplexing and programmable control logic.

A feature of a new electrical distribution system is the relocation of the major distribution buses close to the major loads. This enables much wiring, and thereby weight, to be saved because feeders from the generators to the buses and wiring from the buses to the loads are shortened considerably. Relocation of the buses from the cockpit to nearer the major loads, however, necessitates a means of remotely controlling circuit protective devices and indicating their status. Wiring is needed for that purpose, but can be minimized by multiplexing the control and indication signals (one wire serves several different functions by using a coded signal). Wiring is further reduced by substituting solid-state logic for mechanical relay logic, which is now common in aircraft systems for such control and sequencing functions as extending and retracting the landing gear. That improvement also does away with a large source of failure and maintenance cost--the mechanical relay logic. Besides enabling the achievement of significant reductions in wiring and maintenance costs, the elimination of a significant quantity of wiring might enable structural volume to be reduced allowing further substantial savings in overall aircraft cost.

Moreover, the introduction of a computer would greatly simplify system growth and modification by making the solid-state logic programmable. The computer permits automatic control and load management so as to reduce the need for manual supervision and the consequent possibility of human error, especially during anomalous system operation. The computer also makes system self-test diagnostics possible to further simplify maintenance and enables an aircraft to accommodate new avionics by a simple software change rather than by expensive rewiring.

While the basic technology exists today to achieve many of the advances in the electrical distribution system discussed above, two significant problems must be overcome to make them a cost-effective reality:

- Multiplexing, like many of the current avionics components on an aircraft, requires a computer. The aircraft manufacturers have drawn the line on the proliferation of computers and further development is expected to be delayed until a single computer is developed which will accomplish the functions of the several now in use and provide adequate redundance. Work in this area is in progress.

- Remote control circuit breakers are required to replace manually operated thermal circuit breakers and thereby enable relocation of the electrical load center from the cockpit. Remote control circuit breakers currently cost from $1,000 to 2,000 each using limited, exotic manufacturing techniques and although their price will drop dramatically when they get into full production, they will never be as cheap as thermal circuit breakers which cost from $50 to 300 each.

H. INTEGRATED PNEUMATIC SYSTEM

Integrated pneumatic system (IPS) is a term often applied to the combined pneumatic, air conditioning, anti-icing and auxiliary power systems. Although these systems are treated separately in Military Standard 1374 (except for the pneumatic system which is combined with the hydraulic system) the manufacturers and their major subcontractors consider them as part of a single system because of their commonality. In some cases an aircraft manufacturer will have a single subcontractor oversee the design and production of all of these systems. The systems which comprise the IPS are discussed below. Although cost information is presented for each system separately, cost estimating relationships are developed jointly because much of the cost data are interrelated.

Pneumatic System Description

The pneumatic system includes all heat exchangers and ducting which carries pressurized air from each of the main engines and from the auxiliary power unit (APU). The pneumatic system provides compressed air for cabin pressurization, air conditioning and ventilation, engine starting, ice prevention on critical aerodynamic surfaces and turbine driven supplementary or emergency hydraulic power. To perform these functions, each turbine engine is equipped with a bleed air extraction system. The bleed air control system regulates the pressure and temperature of air supplied to pneumatic accessories and to the air conditioning system. The pressurized air is distributed by a comprehensive ducting, suitable pneumatic ground service connections, necessary controls and isolation and check valves. Each engine normally supplies a corresponding air conditioning unit and anti-ice system, but isolation valves are arranged such that air can be cross-fed from any engine to any system or engine starter. In the event of an isolation valve failure, it can be locked closed without affecting the crossfeed and distribution capability of the system.

Pneumatic System Costs

Heat exchangers, valves and controls contained in the pneumatic system cost between $150 and 250 per pound according to subcontractor data. This value is supported by data for other, similar components included throughout the IPS.

Air Conditioning System Description

The term "air conditioning system" has been replaced by the more technically correct term "environmental control system" (ECS) when applied to modern transport aircraft. In addition to supplying conditioned air to the cabin, flight station, galley and lavatories; the ECS provides cabin pressurization, heats the cargo compartment and supplies conditioned air for avionic and electrical load center cooling.

Air Conditioning System Cost

Subcontractors provided detailed ECS cost data for recent wide body commercial transports. When divided by the appropriate weights, costs per pound of $152, 167 and 184 were indicated. Installation material, ducting and miscellaneous values and controls were not included in the weight or cost.

The cost of air conditioning has decreased dramatically since 1967 when manufacturers indicated that the average cost per pound was about $275 (in then-year dollars).* Increased competition in the ECS business was cited as the major reason behind this significant cost reduction as it spurred technological advances. High fuel costs are now causing new concepts and design considerations which could have an impact on the cost of future ECSs, but is is too early to determine the probable magnitude.

Anti-Icing System Description

Anti-icing functions can be performed by either hot bleed air or electrical heat. Bleed air systems, which are the most common, include all ducting from the main pneumatic source and inner skins which form the hot air cavities along the leading edges of the surfaces. Electrical systems include the electrical blankets fastened to the outer surfaces of critical surfaces plus all wiring and controls.

* Using the DoD inflation factors provided in Table 4.1, this is equal to $520 per pound in 1975 dollars.

Anti-Icing System Cost

Specific cost data were not obtained for either type of anti-icing system. The cost of bleed air anti-icing systems is believed to be similar to the cost of the other systems included in the IPS because it is composed of similar items.

Auxiliary Power Plant System Description

The auxiliary power plant system supplies all power for ground operations in lieu of ground support equipment. These operations include: ground air conditioning, engine starting, air turbine motor driven hydraulic pumps for hydraulic power and driving a generator for electric power. In addition to allowing ground self-sufficiency, the auxiliary power plant system may be used in flight to provide emergency or supplemental power for air conditioning, hydraulic services or critical, electrically powered components. When the auxiliary power plant is expected to be operated in flight, FAA regulations require that it be enclosed in a stainless steel housing for fire protection and this enclosure is considered as part of the auxiliary power plant system.

The auxiliary power system includes the auxiliary power unit (APU), fireproof enclosure, air induction and exhaust, piping and auxiliary backup components such as starter, battery and generator.

Auxiliary Power Plant System Cost

Subcontractors provided two different cost estimates for APUs. One indicated a range of $50,000 to 90,000 per unit with a typical cost of about $75,000. The other estimated a cost of more than $100,000 per unit. Follow-up investigation indicated that the lower range included APUs for smaller and medium sized aircraft while the higher cost applied to APUs for wide body aircraft. Thus, an overall range between $50,000 and $125,000 per APU is appropriate. When the costs were divided by the APU weights indicated in detailed weight breakdowns, a cost range of from $100 to 200 per pound resulted. Further, data on APU engine costs presented in the previous study[6] indicated costs between $145 and $200 per pound. Since the cost of the engine exceeds half the total cost of the auxiliary power plant system, a cost range of $125 to 180 per pound was estimated.

APU cost estimates are sensitive to engine size, installation requirements such as fire protection and the accessories that it drives. Noise reduction is of increasingly greater concern within the aircraft industry and added measures to combat noise could significantly increase the cost of future APUs.

Other Sources of Auxiliary and Emergency Power

In addition to the auxiliary power plant, other sources of auxiliary and/or emergency power are occasionally used on aircraft. These sources include: air turbine motors, controlled speed motors and emergency power units. Since these are not standard equipment on most transport aircraft, they are not included in the cost estimating relationships. However, a brief discussion and general cost information on these items are provided below for information.

The air turbine motor (ATM) has been used for auxiliary or peaking power requirements such as a hydraulic power assist for takeoff and landing on wide body aircraft and offers redundancy as a backup system for the main engine driven pumps. ATMs can provide rotor, hydraulic or electrical power depending upon the driven accessories (generator, pump, etc.) that are connected to them. The use of ATMs by the primary manufacturers of commercial transports varies significantly. For example: Boeing has an ATM for each of the four hydraulic systems on the 747; Douglas does not use them; and Lockheed has two for the four hydraulic systems on the L-1011.

Controlled speed motors are variable angle, positive displacement hydraulic motors with built-in speed control. They are used to provide accurate and stable constant speed power for operating aircraft generators from a hydraulic power supply. Controlled speed motors can function as an auxiliary power electrical supply for multi-engined aircraft, as a prime electrical source for small aircraft or as an emergency source of electric power on any aircraft. Some discussions with airframe manufacturers have been held regarding the use of controlled speed motors on future commercial aircraft. Controlled speed motors are, however, less efficient than other means of obtaining auxiliary power because they cause hydraulic power losses. In practice, CSMs are typically used on military aircraft for backup power to emergency systems.

Emergency Power Units (EPUs) are used only in emergency to start the engine and provide hydraulic power to operate the control surfaces. They are an alternative to Ram Air Turbines. Emergency power units can use either stored monopropellant (70 percent hydrazine and 30 percent water) or engine bleed air or mixed mode of operation in which monopropellant is added to supplement the air mode when available engine bleed air conditions cannot satisfy demand. Emergency power units consist of a catalytic decomposition chamber that generates gases which drive an impulse turbine that it integrated with a gearbox. The output then supplies power to drive a generator or hydraulic pump. EPUs are completely self-contained and require only a 28 volt DC signal to initiate operation, but they must be recharged on the ground after each use. The Concord is the only commercial transport with an EPU; however, EPUs are included on non-transport aircraft like the F-4, F-14, F-15, F-16 and F-18.

Costs of Other Sources of Auxiliary and Emergency Power

Typical ATM costs (exclusive of driven accessory) vary from $8,000 to 10,000 for a 10-horsepower unit without automatic controls to $25,000 to $30,000 for a 90-horsepower unit that includes automatic controls. Costs vary within the ranges indicated in accordance with horsepower rating, controls and types of engine driven output provided.

Controlled speed motors cost about $12,000 to $15,000 each. They are of extraordinarily high quality because of their design and required high reliability as emergency equipment.

Subcontractors were unwilling to discuss EPU costs in even the most general terms because they are new and the market place is extremely competitive.

Integrated Pneumatic System Costs

By using detailed weight statements, the composition of the IPS was determined as a percent of total system weight for each of the four classes of aircraft indicated in Section 2C. This breakdown is provided in Table 4.13. These data indicate that the pneumatic system constitutes a smaller percentage of total IPS weight for small commercial aircraft than for other types (8 percent compared to about 20 percent) and that the anti-icing system weight is a greater percentage for small commercial aircraft and less for wide body commercial aircraft than for the other types (24 percent and 7 percent respectively compared to 15 percent). Reasons for these differences are not known. As might be expected, the absolute IPS weight increases as the size of the aircraft increases but as a percent of MEW it decreases from 4.7 percent for small commercial aircraft to 2.6 percent for wide body commercial aircraft.

The costs for "miscellaneous material" (pneumatic system ducting and supports; the air conditioning distribution system; and the auxiliary power plant engine mounts and enclosure) were not discussed above. They were assumed to cost between \$25 and 75 per pound based on the rationale provided for similar items in Section 4F. Table 4.13 summarizes cost information for key components of the IPS; the average cost per pound of the IPS is about \$115.

Cost information and confidence values for the individual systems which comprise the IPS are presented in Table 4.14. The cost ranges for each system often vary markedly by aircraft size because they are affected by the design and mix of components as discussed above. Instances where confidence values are low reflect the necessity of making assumptions regarding some IPS components. The costs presented in Table 4.14 represent subcontractor costs only. In order to determine a total system level cost, these costs

Table 4.13

INTEGRATED PNEUMATIC SYSTEM (IPS) COST

Major Component or Subassembly	Component Percent of Total System Weight: Small	Medium	Military Transport	Wide Body	Cost per Pound	Confidence Value
Pneumatic	8.3%	20.4%	17.1%	21.3%		
Heat Exchangers	1.5	7.6	5.8	6.1	$150-250	7
Ducting and Supports	6.8	12.8	11.3	15.2	25-75	3
Air Conditioning	39.7	43.5	45.7	48.9		
Environmental Control System	16.4	13.5	11.1	14.3		
Misc. Valves, Regulators, Controls	4.8	9.6	12.8	8.3	152-184	9
Cargo Heat/Cool System	0.5	0.7	NA	3.6		
Distribution System	18.0	19.7	21.8	22.7	25-75	3
Anti-Icing	24.2	15.5	15.0	6.6	100-160	4
Auxiliary Power Plant	27.8	20.6	22.2	23.3		
APU	21.1	12.2	14.5	17.5	125-180	9
Engine Mounts, Enclosure	6.7	8.4	7.7	5.8	25-75	3
Total IPS*	100%	100%	100%	100%		
IPS Percent of MEW	4.7%	4.4%	2.8%	2.6%		
Total IPS Group Weight	2,052	4,156	3,282	6,003		

* Weighted average. See footnote to Table 4.2.

Table 4.14

INTEGRATED PNEUMATIC SYSTEM

COST BY AIRCRAFT TYPE

	Small		Medium		Military Transport		Wide Body	
Systems	CER	Confidence Value	CER	Confidence Value	CER	Confidence Value	CER	Confidence Value
Pneumatic	\$ 48-107 (avg. \$75/lb.)	4.9	\$ 72-140 (avg. \$106/lb.)	5.8	\$ 67-134 (avg. \$101/lb.)	5.7	\$ 61-125 (avg. \$93/lb.)	5.5
Air Conditioning	94-134 (avg. \$114/lb.)	7.8	108-146 (avg. \$127/lb.)	7.8	91-132 (avg. \$112/lb.)	7.7	93-134 (avg. \$114/lb.)	7.8
Anti-Icing	92-139 (avg. \$116/lb.)	4.0	93-143 (avg. \$118/lb.)	4.0	86-136 (avg. \$111/lb.)	4.0	88-137 (avg. \$113/lb.)	4.0
Auxiliary Power Plant	101-155 (avg. \$128/lb.)	8.4	84-138 (avg. \$111/lb.)	7.9	91-144 (avg. \$118/lb.)	8.1	100-154 (avg. \$127/lb.)	8.4
Total IPS	\$ 92-139 (avg. \$116/lb.)	6.9	\$ 93-143 (avg. \$118/lb.)	6.8	\$ 86-136 (avg. \$111/lb.)	6.9	\$ 88-137 (avg. \$113/lb.)	7.3

were adjusted by an approximate factor of 1.33 as discussed in Section 2C. The adjusted cost data were used to develop the four cost estimating relationships shown in Figure 4.8.

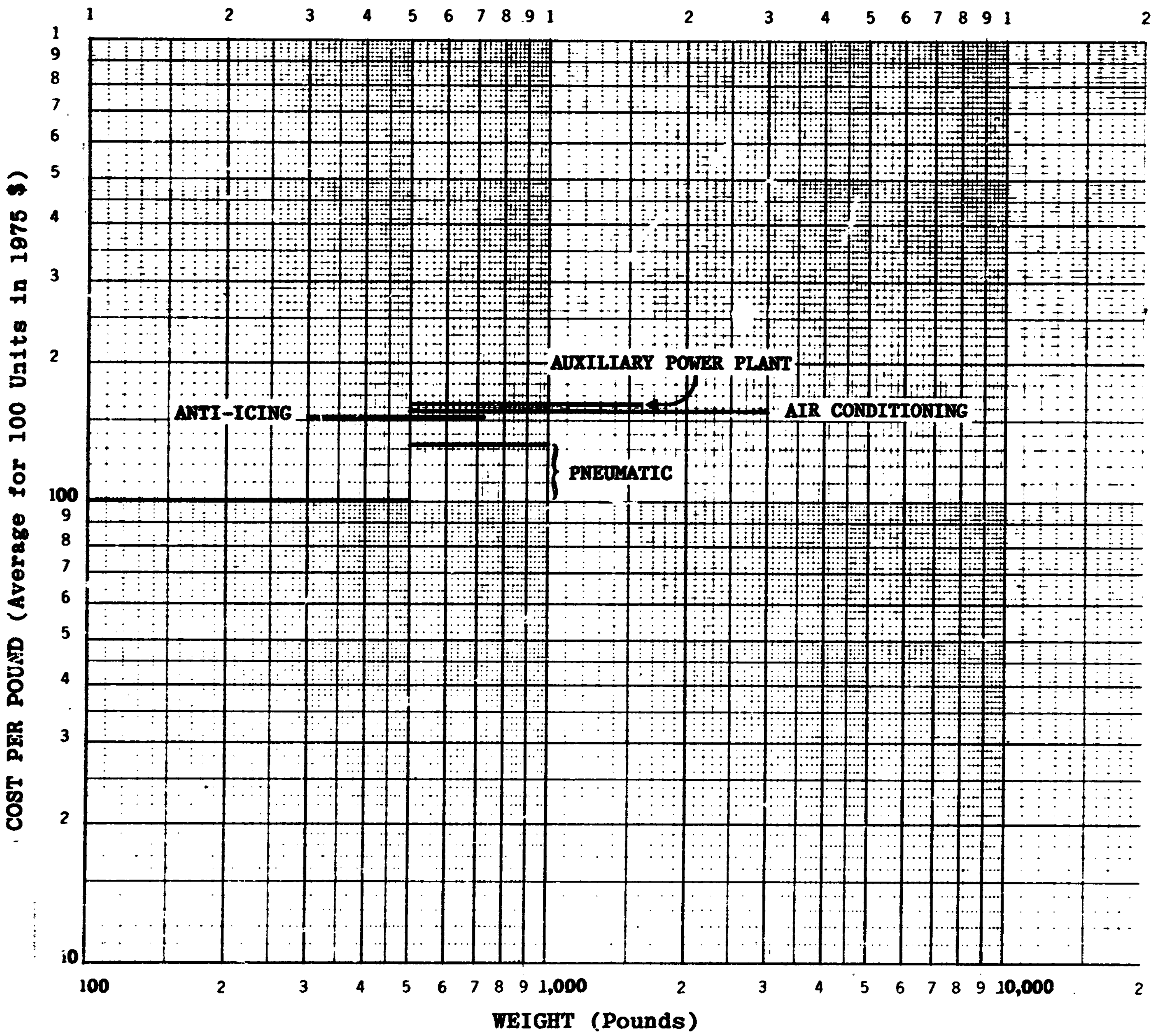


Figure 4.8 INTEGRATED PNEUMATIC SYSTEM CERs

I. FURNISHINGS AND EQUIPMENT SYSTEM

System Description

Furnishings and equipment includes a variety of items in the cockpit, main cabin and cargo compartment. In the cockpit, this category includes all instrument and console panels, seats, insulation, lining, crew oxygen system, and cockpit door and partitions.

In the main cabin of the commercial aircraft, this category includes seats, floor covering, insulation, side panels, ceiling structure, hatrack or baggage containers, complete lavatory installation, complete galley installation including food container inserts, ovens, refrigerators, food carts, window shades, divider partitions, stowage provisions for luggage and magazines, passenger cool air and call buttons, stewardess seats, and passenger oxygen system including portable emergency oxygen bottles. Passenger reading lights are included with the electrical system and discussed with it. The entertainment system is included in the avionics system.

In the cabin of military aircraft, the furnishings and equipment category includes insulation and lining, troop seats, litters, crew bunks, galley and lavatory, floor covering, cargo and aerial delivery system (winches, pry-bar, tie-down fittings), equipment stowage and troop oxygen system.

In the belly of the commercial aircraft, this category includes insulation and lining and cargo loading system. The cargo containers are not included as they are operator's items.

Miscellaneous items include the engine and cabin fire extinguisher systems, fire warning system, exterior finish, and miscellaneous emergency equipment (i.e., first aid kit and fire ax). Emergency exit slides and life rafts are not included as they are operator's items.

System Costs

Cost and technical characteristics related to cost are discussed below for the major furnishings and equipment components including: seats, interiors, galleys, lavatories, toilets, oxygen system and other interior equipment. Cost estimating relationships are then developed for the complete furnishings and equipment system.

Aircraft Seating

Seating represents a significant cost and weight. Passenger seats are chiefly custom items on commercial aircraft varying in accordance with each customer's wants and needs. While aircraft manufacturers make a "house" aircraft where the purchaser does not have an option as to the type and quality of equipment (including seats), airlines almost always select a unique seat design. In fact, airlines frequently have several models of seats on their various aircraft types. For example, TWA currently has at least five different models of seats as it has elected newer designs for newer aircraft rather than selecting a standard seat design for all of its aircraft.

The seat frame is typically a standard item even though features such as chromed or recessed legs may be added as options. The cost of the frame is relatively low because of large production volume. The seat covering and special features such as entertainment units, trays, or breakover are the primary determinants of cost. It was noted that U.S. airlines generally buy about the same quality seat and, therefore, pay about the same price. Foreign airlines, on the other hand, often order cheaper and lighter seats.

It is stated that the weight of furnishings (including seats) is viewed by aircraft manufacturers with the same concern as the weight of other systems. Evidence does not entirely support this contention, however, as the weight of coach seats has been reduced dramatically from about 130 pounds per triple seat provided on one of the first 707s to a current weight of less than 65 pounds per triple seat while the weight of a first class seat has remained at about 45 pounds per seat bottom. The airlines are apparently unwilling to sacrifice any luxury in first class even at the opportunity of saving several hundred pounds not to mention cost.*

* For example, by reducing the weight of a first class seat from 45 to 34 pounds (it would still be 1.5 times heavier than a coach seat), the weight of an L-1011 with 20 percent first class seating (52 passengers) could be reduced by nearly 600 pounds.

Table 4.15 provides representative costs and weights for several types of aircraft seats. The cost indicated for passenger seats ($600) is the average cost including some optional accessories such as fold down center seat backs. The cost of seats without accessories is about $550 per seat bottom and may be increased to about $700 by adding optional items. Both the cost and weight of coach seats vary in accordance with whether they are double or triple as double seats cost and weigh 78 percent as much as triple seats rather than 67 percent as might be expected. Thus, if an unusual seating configuration is called for, the cost estimate should be appropriately adjusted.

The high cost per pound indicated for flight attendant seats on Table 4.15 is because of special featues and the fact that they are made in very limited quantities.

<u>Interiors</u>

There is a little difference in the cost of interiors (including: paneling, lining and trim; utility racks and passenger service units; partitions and doors; utility trays and divider tables; coat rooms and stowage) among aircraft of comparable size and function. This is chiefly due to the fact that materials are similar consisting primarily of aluminum honeycomb, fiberglass and metal bonded parts.

Limited cost data were available for interiors. These data include a newer aircraft, the DC-9-50, and a retrofit of the 727/100 for United Air Lines to provide "wide body styling." These costs are presented in Table 4.16. Since the DC-9-50 and 727/100 are about the same size (the DC-9-50 is slightly larger), the difference in cost is surprising. This can be explained by the fact that the DC-9-50 interior was built from aircraft manufacturer designs and the 727/100 retrofit interior was designed and built by the subcontractor. Also, the 727/100 cost includes items which were not supplied on the DC-9-50.

Since the design and construction of aircraft interiors is similar, a cost estimating relationship for interiors covering the area from the floor

Table 4.15

REPRESENTATIVE COSTS OF AIRCRAFT SEATS

Seat Type	Cost per Seat Bottom	Weight (Pounds)	Cost per Pound
First Class Passenger	$1,300	45	$29
Coach Passenger	600	22	27
Flight Attendant	1,500	18	83
Pilot (military)	2,100	58	36
Crew (military)	1,550	52	30

Table 4.16

COSTS OF RECENT AIRCRAFT INTERIORS

Item		Cost	Comments
DC-9-50	Side Walls and Window Reveals	$20,000-25,000	
DC-9-50	Storage Bins, Cabin Lighting and Sculptured Ceiling Panels	110,000	Since lighting is part of electrical system, reduce by 25% to determine interior cost only.
727/100	Complete Interior	225,000	Includes equipment such as passenger service units and amortized design and tooling costs.

on one side to the floor on the other side might appropriately be based on length. About $1,500 per linear foot would be a reasonable amount for aircraft of normal width (six across seating) and would include side walls, window reveals, storage bins and sculptured ceiling panels but exclude lighting and passenger service units. A cost estimating relationship based on linear feet for wide body aircraft interiors would be greater only by the greater width of the ceiling panels as all other components are comparable. A wide body ceiling is approximately seven feet wider than a normal ceiling. However, even this difference might be offset by designs which incorporate additional lighting fixtures in lieu of ceiling panels.

Galleys

Galleys are made in modular units which fit the space available on each aircraft type. Like other furnishings, galleys are regarded as marketing tools by the airlines because they affect the service that is provided. They are, therefore, frequently modified to suit the customer.

Although galley design is not affected by the design of other furnishings and equipment components, it is greatly dependant of trends established by food purveyors. For example, the current trend is the extensive use of frozen foods which has meant more use of microwave ovens.

There are two general types of galleys, those for wide body aircraft which have upper and lower facilities and those on other aircraft such as DC-8 and 737 which are completely contained in the passenger cabin.

A representative cost for a complete 747 galley* is about $700,000, but this cost can range from less than $400,000 to more than $1,000,000 depending on the desired class of service and manner of food preparation. A complete DC-10 galley which includes a service center, aft bar and lower facility

* Including: galley, ovens, coffee makers, refrigerators, bar and tray carriers or trolleys (carts).

costs about $250,000. The cost of DC-10 galleys are significantly less than for 747 galleys because they feed fewer people (200 vs. 450) and because flights are generally of shorter duration. Other example costs are about $50,000 to $100,000 for DC-9 galleys and $100,000 to $125,000 for 727 galleys.

Lavatories

Lavatory design often differs from manufacturer to manufacturer as, for example, Douglas integrates solid, structural walls into its lavatories while other manufacturers use modules that are simply bolted into place as a complete unit. Further, the layout of lavatories differs according to the "footprint" of the space in which they are to be placed. The 747 has potential locations for as many as 17 lavatories; however, the purchaser may require as few as eleven. There is, of course, a tradeoff between the number of lavatories and the number of seats.

A typical lavatory module costs between $10,000 and 15,000.

Toilets

The various lavatory locations on a particular aircraft influence the design of toilet tanks and vents such that several different toilet tank configurations may be required for one aircraft. Design options are available for toilets, as for example, the 747 has double toilets with a wall between them and the L-1011 uses common tanks for several toilets. Although common tanks were tried on the DC-8 and again on the DC-10, they had inherent functional problems and were soon eliminated early in production. Reduced ground service time requirements are a major advantage of the common tank.

Materials technology as well as innovative designs has significantly affected the structure of aircraft toilets. The first recirculating flush toilets were on the 707 and DC-8 and used heavy stainless steel for both the tanks and tops. Fiberglass tanks and tops are now used along with many plastic components and unit weight is reduced to less than half that of the original 707 toilets. Unit weight has, however, remained fairly constant in recent years and is at a point where further weight reduction efforts could impair structural or functional integrity.

Table 4.17 presents cost data for aircraft toilets. The cost of toilets varies between $1,500 and 3,000 depending upon size, sophistication and quality of motor, pump, filter, drain and valve. An average cost of $2,000 is representative of most current units.

The next technological advance in aircraft toilets is likely to be vacuum flush which is under consideration for the next generation of commercial aircraft. Vacuum flush would have a central tank and would enable fluid to be filtered and reused, thereby substantially reducing flushing the weight of fluid carried. Further, only one ground service point would be required and maintenance costs would, thereby, be reduced.

Emergency Oxygen

Emergency oxygen systems are required to enable the flight crew and passengers to maintain a state of useful consciousness in the event that decompression occurs at a high altitude.

Emergency oxygen has typically been provided by fixed gaseous oxygen breathing equipment consisting of tanks containing compressed oxygen and a regulation and distribution system. Newer technology has been used on the C-5 and L-1011 to provide miniature, individual sodium per-chlorate chemical oxygen generators. This concept eliminates the use of oxygen storage cylinders, multiple pressure reducers, automatic regulators, and extensive distribution plumbing with associated connectors and valves. Accordingly, its cost and weight is considerably reduced. Safety is greatly improved by eliminating handling of high pressure gaseous oxygen and minimizing the quantity of high pressure gaseous oxygen available at any single location. In the event of a general aircraft fire, chemical generators will not burn in the "blow torch" fashion of high pressure oxygen and, being inert until activated, will not create or support a crash fire. Standard, continuous flow passenger oxygen masks are automatically presented at each passenger seat

Table 4.17

COSTS OF AIRCRAFT TOILETS

Toilet Type	Cost	Comments
Executive Jet and Military Transports	$ 700-800	
707	3,500	Old technology stainless steel construction.
L-1011	2,300	Total cost of 7 toilets is $16,000.
Estimating Range for Commercial Transport Toilets	1,500-4,000	

location, cabin attendant station, galley station and lavatory, whenever cabin altitude exceeds approximately 12,500 feet.

Recent costs for the components of a bottled gas emergency oxygen system are provided in Table 4.18. The total system cost is primarily a function of the number of passengers.

Furnishing and Equipment Costs

Using detailed weight statements, the composition of the furnishings and equipment system was determined as a percent of total system weight for the three classes of commercial aircraft defined in Section 2C. These breakdowns are provided in Table 4.19. As indicated, the composition of this system is relatively consistent for the three classes of commercial aircraft with the following notable exceptions:

- As the aircraft size increases, galley equipment and structure becomes a greater percentage of the total system weight (from 5 to 19 percent). This is as expected because complete meals are not commonly served on the smaller aircraft which fly shorter routes.

Table 4.18

COSTS OF EMERGENCY BOTTLED GAS OXYGEN SYSTEM COMPONENTS

Crew System

Item	Unit Cost	Typical Quantity Required	Total Cost
Crew Regulators	$400	5	$2,000
Cylinder and Valve	175	1	175
Pressure Reducer	150	1	150
Exchange Recharge Valve	150	1	150
Gauge Assembly	50	1	50
Miscellaneous	25	1	25
Subtotal			$2,550

Passenger System

Item	Unit Cost	Typical Quantity Required	Total Cost
Cylinder and Valve	$175	2-3	$ 350-525
Composite Regulator	800	2	1,600
Latch Valve Manifold	30	1 for each row of seats	1,200-4,800
Masks	10	1 for each passenger	1,000-4,000
Portables for Emergency	130	7-14	910-1,820
Subtotal			$5,060-12,745
Total Oxygen System Cost			$7,600-15,300

Table 4.19

FURNISHINGS AND EQUIPMENT SYSTEM COST

Major Component or Subassembly	Component Percent of Total System Weight: Small	Medium	Wide Body	Military	Cost Per Pound	Confidence Value
Seats	37%	37%	37%	20%		
Passenger	34	35	35	13	$ 25-32	9.5
Crew	3	2	2	7	{30-36 (military) 38-45 (commercial)	7.5
Accommodations and Furnishings	63%	63%	63%	80%		
Lavatory Equipment	4	5	4	2	16-35	8
Fresh Water System	1	1	2	1	12-26	3
Cargo Handling	1	1	4	11	60-80	2
Galley Equipment and Structure	5	9	19	6	100-150	8
Floor Covering	4	4	3	1	3.50-4.50	8
Thermal/Acoustic Material	12	13	7	21	28-60	3
Flight Crew Accommodations	2	1	1	4	42-91	2
Oxygen System	3	3	2	11	51,44,28	8
Interior*	32	27	21	23	42-91	
Total Furnishings and Equipment**	100%	100%	100%	100%	$ 35-70 ($ 53 avg.)	7.2
Furnishings and Equipment Percent of MEW	13.3%	13.6%	14.5%	[illegible].4%		
Total Furnishings and Equipment System Weight (average pounds)	5,849	14,325	33,166	4,456		

* Includes: paneling, lining and trim; utility racks and passenger service units; partitions and doors; utility trays and divider tables; coatrooms and stowage.

**Weighted Average. See footnote to Table 4.2.

- Thermal/acoustic material and interior become a smaller percentage of the total system weight as the aircraft size increases (from 44 to 28 percent).

- Cargo handling equipment is insignificant on small and medium sized commercial aircraft, but constitutes four percent of the system weight for wide body commercial aircraft. It is assumed that this equipment is a function of length of trip. Also, perhaps, advanced technology has enabled the economical substitution of capital equipment for manual cargo handling labor on the wide body aircraft.

- It is noted that furnishings and equipment as a percent of MEW increases slightly with the aircraft capacity (from 13.3 to 14.5 percent). This increase results from the increased passenger services that are offered on wide body aircraft.

While the commercial aircraft considered are all passenger aircraft, the military transport aircraft included in the furnishing and equipment breakdown on Table 4.19 (C-130E, C-135B, C-141A, C-133B and C-5A) perform a variety of transportation functions including strategic and heavy logistics, airborne refueling and troop transportation. Thus, furnishings and equipment on military transports represent a much smaller portion (3.4 percent) of MEW than they do on commercial aircraft.

Cost per pound estimates of furnishings and equipment system components are also provided in Table 4.19. The following discussion indicates the bases for these estimates:

- The costs per pound for seats are based on data provided in Table 4.15 and in the related discussion. Thus, the range for passenger seats ($25 to 32) was determined by dividing the cost per seat range ($550 to 700) by the average weight (22 pounds). The average cost per pound of first class seating ($29) is within the range.

- Crew seat data were available for military aircraft only. Since these seats are not as sophisticated as commercial crew seats, their cost per pound ($30 to 36) was increased by 25 percent (to $38 to 45) to reflect the additional sophistication of commercial seats.

- The costs of lavatory equipment (toilets and tanks, etc.) are provided in Table 4.18 and in the related discussion. A range was calculated using old technology (707 average unit cost of $3,500 divided by average weight of 214 pounds equals $15 per pound) and new technology (L-1011 average unit cost of $2,300 divided by average weight of 66 pounds equals $35 per pound). As noted above, these represent extreme values with the newer (L-1011) technology thought to be more representative.

- No specific cost data were available for the fresh water system; however, a review of system diagrams indicated that it was less complex than the toilet system. Therefore, the range used for the toilet system was reduced by about 25 percent and a cost of between $12 and 26 per pound was assumed for the fresh water system.

- The cargo handling system includes mechanical rolling devices and the drive mechanism for them. No specific cost data were obtained for these; however, companies manufacturing mechanical flight control actuators also make cargo systems and they are similar in composition. It was, therefore, assumed that their cost is the same as mechanical flight control actuators ($60 to 80 per pound).

- Typical galley costs range from about $100,000 for medium sized aircraft to about $700,000 for wide body aircraft. Corresponding weights are about 800 and 6,300 pounds respectively. Thus, a cost of between $100 and 150 per pound is appropriate.

- Floor covering in an aircraft is of high commercial quality to withstand concentrated use and to comply with strict FAA fire retardant regulations. A non-aircraft carpet supplier indicated that a range of $15 to 20 per yard would be appropriate. By using interior dimensions and dividing by total floor covering weight, it was determined that 4.5 pounds per square yard was a representative and consistent weight. Hence, $3.50 to 4.50 per pound is a reasonable cost for floor covering.

- No specific cost data were obtained for thermal acoustic material. Thus, the assumption was made that its cost is about two-thirds as much as the interior ($28 to 60 per pound).
- Flight crew accommodations consist of items such as consoles and pedestals. Since no cost data were available for them, they were assumed to cost the same as the cabin interior ($42 to 91 per pound).
- The detailed cost for a fixed gaseous aircraft oxygen system is provided in Table 4.18. By dividing the low and high costs ($7,600 to 15,300) by typical weights for oxygen systems for aircraft of those sizes (150 and 550 pounds, respectively) costs of $51 and 28 per pound are determined for small and large aircraft systems. A cost per pound of $44 ($13,800 divided by 316 pounds) was calculated for medium-sized aircraft.
- As indicated, the interior is composed of many items. It is felt that the interior costs provided in Table 4.16 and in the relevant discussion are representative for all of the items contained in this category. Weights for the paneling, lining and trim, utility racks and passenger service units and coatrooms and storage for the DC-9-50 (2,590 pounds) are divided into the cost for these items ($107,500) and comparable weights for the 727-100 (2,483 pounds) are divided by their cost ($225,000), which results in a range of $41 to 92 per pound. This is thought to represent two extremes as the weights for the DC-9-50 may include items which might not be included in the cost (thereby increasing the lower value) and the weights for the 727-100 may exclude items included in the cost (thereby reducing the higher value).

Table 4.20 provides costs and confidence values for the furnishings and equipment system for each of the four classes of aircraft defined in

Table 4.20

FURNISHINGS AND EQUIPMENT SYSTEM

COST BY AIRCRAFT TYPE

	Small	Medium	Wide Body	Military
CER	$ 35-62 (avg. $49/lb.)	$ 37-63 (avg. $50/lb.)	$ 43-70 (avg. $57/lb.)	$ 40-67 (avg. $54/lb.)
Confidence Value	7.0	7.2	7.3	5.0

Section 2C. The variance in the furnishings and equipment system costs and the confidence values is caused by the different mix of components by weight found on the four sizes of aircraft as discussed above. Further, since most of the cost data were obtained for commercial aircraft and its applicability to military transports is somewhat questionable, the confidence value for military transport aircraft furnishings and equipment is much lower than for commercial aircraft (5.0 instead of 7.0 to 7.3).

The costs presented in Table 4.20 represent subcontractor costs only. In order to determine a total system level cost, these costs were adjusted by an approximate factor of 1.33 as discussed in Section 2C. These adjusted cost data were used to develop the cost estimating relationship shown in Figure 4.9.

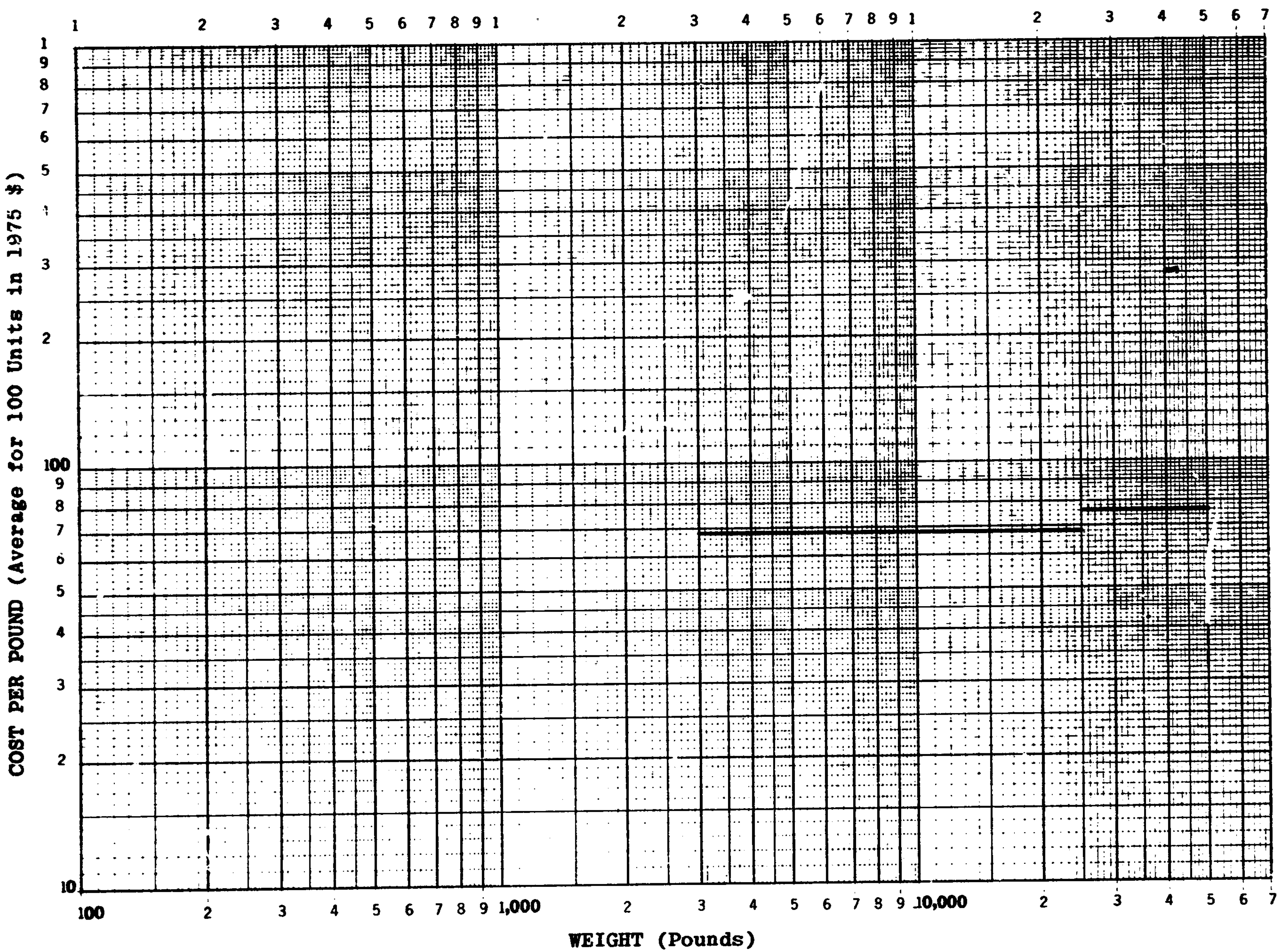


Figure 4.9 FURNISHINGS AND EQUIPMENT SYSTEM CERs

J. INSTRUMENTS AND AVIONICS SYSTEMS

Although they are separate systems, instruments and avionics are discussed together because they have many similarities.

Systems Description

Instruments perform basic monitoring and warning functions associated with the flight of the aircraft, control surface positioning, electrical, hydraulic and pneumatic systems operation, engine operation and fuel quantity. The instrument system includes cockpit indicators and warning lights, electronic black boxes as the points of signal input and circuitry between the black boxes and the monitoring devices.

The avionics system is separated into four subsystems as follows:

1. The integrated flight guidance and controls subsystem includes the autopilot system, and associated pitch, roll, yaw computers; the flight director system; the gyrocompass system; the attitude and heading reference system; and the inertial navigation system. These units are interdependent and are, therefore, integrated into one operating unit. Although a part of this subsystem, the auto-throttle/thrust management system is included with the propulsion system because it functions as an engine control. All indicators, servomechanism, and associated circuitry, supports and attachments related to the integrated flight guidance and controls subsystem are also included.

2. The communication subsystem is separated by its internal and external functions.

   a. The internal communication system includes the interphone system, the public address system, and the multiplex (MUX) system. The MUX system is a signal transmission source for the passenger-to-attendant call system, passenger entertainment system, the public address system, the reading light system, the passenger oxygen latch release system and the passenger individual cool air system. The DC-10 and the L-1011 utilize a communication MUX system. All amplification units, head and hand sets, speaker installations, encoders and decoders for the MUX system, and associated wiring, supports and attachments related to the internal communication system are also included.

b. The external communication system includes the radio equipment which is used for aircraft to aircraft or aircraft to ground communications. It is composed of the very high frequency (VHF) system, the high frequency (HF) system, the ultrahigh frequency (UHF) system, provisions for satellite communication, the selective call (SELCA) system, and the voice scrambler system. Most overwater airplanes are equipped with HF or UHF equipment. All radio units, antennas, and associated coax, wiring, supports and attachments related to the external communication system are also included.

3. The navigation subsystem includes all radar equipment, the automatic direction finding (ADF) system, the distance measuring equipment (DME) system, the long range navigation (LORAN) system, the doppler system, the navigation computer systems, the stationkeeping system, the tactical air navigation (TACAN) system, the variable omnirange (VOR) system, the marker beacon system, the instrument landing system (ILS), the collision avoidance system (CAS), the airport traffic control (ATC) system the radio altimeter system, the glide slope system and the radar beacon system. Most overwater aircraft are equipped with LORAN and doppler systems. All of the navigation units, indicators, antennas, associated circuitry and antenna coax, and supports and attachments related to the navigation subsystem are also included.

4. The miscellaneous equipment subsystem includes the flight, voice and crash recorder systems, the aircraft integrated data (AID)/ malfunction detection analysis and recording (MADAR) systems, the weight and balance system, if installed, the equipment rack structure and miscellaneous hardware and circuitry.

System Costs

Instruments and avionics costs are difficult to estimate for several reasons. First, technology is rapidly advancing. Thus, equipment with approximately the same capabilities as in the past may now be built at a lower cost and equipment with recently unattainable capabilities may now be obtained. Second, instruments and avionics perform a variety of functions as noted above and costs may vary significantly by function. Third, avionics is largely a customer option and may vary greatly on a given aircraft model depending upon its mission,* the extent to which the customer wishes to maintain standard equipment within its fleet or any other unique user requirements.

Very approximate costs have been determined for instruments and avionics. These costs are believed to reasonably approximate the cost of instruments and avionics for most transport aircraft. However, if relatively simple or highly complex instruments and avionics systems are contemplated, estimates should be adjusted accordingly.

Instruments and avionics costs are of two distinct types - equipment (e.g. "blackboxes") costs and other costs including installation, hardware, wiring and antennas.

Detailed cost information was available for some instruments and avionics equipment. The cost of government furnished instruments equip-

* For example, military transports generally have more complex and, therefore, more expensive avionics than commercial transports, and commercial transports flying overseas generally have more complex avionics than those flying only domestic routes.

ment for the C-5 and C-141 averaged about $590 per pound.[6] Avionics equipment costs averaged about $650 per pound for a conceptual STOL aircraft.[15] In addition, detailed government avionics cost data for attack and fighter aircraft from an unpublished source indicated the following costs for non-weapon related avionics: radio navigation equipment $1,130 per pound on the average with a range of $130 to $3,990; radar navigation equipment about $960 per pound with a range of $390 to $2,120; communications equipment about $930 per pound with a range of about $40 to $1,670; and airborne computers about $1,510 per pound with a range of $370 to $3,630. Based on a typical mix of these types of equipment for a transport aircraft, an average cost per pound would be approximately $1,000. It is not surprising that this cost for non-weapon related avionics from attack and fighter aircraft is considerably more expensive than the cost of avionics for transport aircraft.

Thus, the typical cost of avionics and instrument equipment on transport aircraft was assumed to be $620 per pound which is an average of $590 and $650. It should be apparent, however, that this cost might be increased substantially or reduced slightly if a more or less sophisticated mix of equipment is required.

No specific cost information was available for "other" costs such as installation hardware, circuitry and antennas. In general these nonequipment items represent about one half of instrument and avionics systems weights. An average cost of $50 per pound was assumed for these items as discussed in Section 4F.*

* Cost data provided in Reference 15, when adjusted to be comparable to costs used in this study, indicated that a cost of $53 per pound was appropriate for instruments and avionics components other than equipment.

The above costs represent only subcontractor costs. In order to determine a total system level cost, they were adjusted by an approximate factor of 1.33 as discussed in Section 2C. The adjusted cost data were used to develop the cost estimating relationships shown in Figure 4.10. The brackets indicate the approximate range of weights for instruments and avionics.

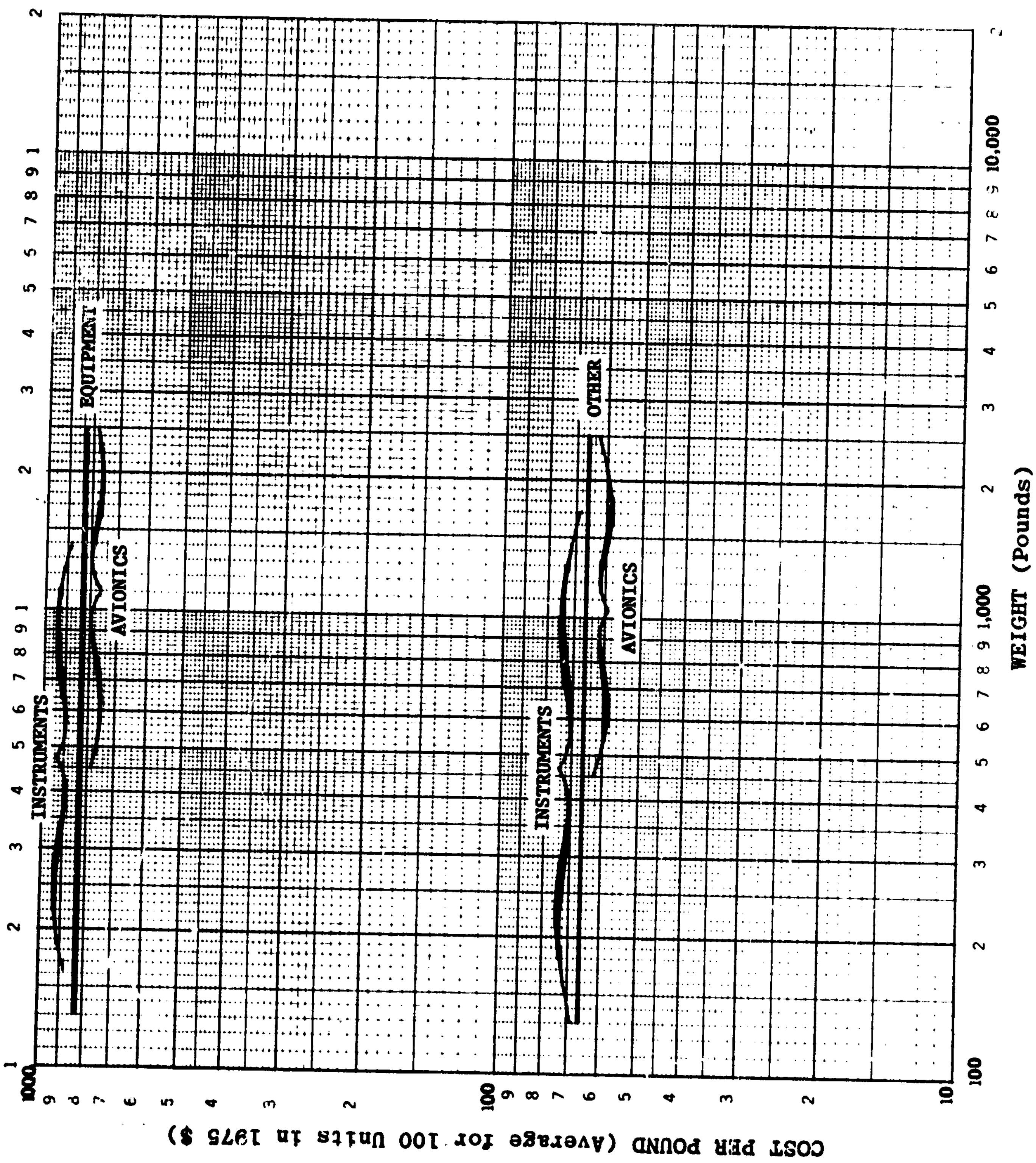


Figure 4.10 INSTRUMENTS AND AVIONICS SYSTEMS CERs

K. LOAD AND HANDLING SYSTEM

System Description

The load and handling system consists of fittings and structural provisions for jacking, hoisting and mooring. Some military aircraft have stabilizer jacks to hold the aircraft in a rigid position during cargo loading.

System Costs

The load and handling system represents an insignificant cost in the production of an aircraft (less than 0.1 percent). As such a minor item, no independent research was devoted to this system. Because of its similarity to and location in the body, it was assumed to have the same cost per pound.

L. FINAL ASSEMBLY

Final assembly costs constitute a significant portion of the total cost of an aircraft. As discussed in Section 2C, 25 percent of the subcontractor costs including system-level assembly is considered a reasonable approximation of this cost.

SECTION 5

DETAILED SYSTEM WEIGHT ANALYSIS

The weight estimating relationships (WERs) derived in this study were summarized in Table 3.1. In this section, the development of each WER is discussed in detail. WERs were derived for each aircraft system, as well as for major components of several of the systems. Each system was described in Section 4 and a summary of these descriptions is presented in Appendix C. These system descriptions correspond exactly to the standard weight groups defined in Military Standard 1374, except that the Military Standard combines hydraulics and pneumatics as one standard weight group and includes the autopilot with flight controls.*

In the following subsections, weight and design or performance characteristics for existing aircraft are presented for each system, and the derivation of the WER or WERs is discussed. Special attention has been given to small transport aircraft (take-off gross weight of approximately 150,000 pounds or less), and where appropriate separate WERs are derived to better predict weights for small aircraft. The special symbols used in this section were defined in Table 3.2.

In general, data are presented for 19 commercial and 7 military transports including different models of some of the aircraft. Three study aircraft (the MDAT, SCAT-15, and AST(M)) are included in order to provide a more comprehensive data base. The sources of weight data for each of the aircraft considered were presented in Table 3.5.

In the various tables in this section, subtotals and totals for the weight data are indicated by the symbols and by the level of indenture of the descriptive term (i.e., the closer to the left hand margin the more aggregate the data).

---

* Leaving the autopilot as part of the flight controls system would have required the arbitrary distribution of the flight guidance and control system weight on newer aircraft between flight controls and avionics systems; whereas, the autopilot weight for older aircraft was readily available.

A. WING, TAIL AND BODY SYSTEMS

Wing, tail and body systems have similar designs and use similar materials and methods of fabrication.

Weight and Design Characteristics

Weight and design characteristics are presented in Tables 5.1 and 5.2 for 19 commercial and 7 military transports, respectively.

Weight Estimating Relationships

Wing:

The wing weight is sensitive to several wing design and geometry characteristics. It has been shown that these variables can be combined into a wing design equation which for this study is called the bending material weight index. This index, which is familiar to weight engineers, is:

$$I_w = \frac{U\,(AR)^{1.5}(ZFW/TOGW)^{0.5}\,(1+2\lambda)(W/S)\,S_w^{1.5}10^{-6}}{(t/c)\,(\cos\Omega_{c/4})^2\,(1+\lambda)}$$

This index is related to the wing box structure weight; the higher the index, the higher the wing box structure weight required. The remainder of the wing weight, the secondary structure weight, is related to the wing area (S_w).

Therefore, the wing weight (W_1) was correlated with the bending material weight index (I_w) and the wing area (S_w). For medium and large aircraft (S_w greater than about 900 square feet), wing weight correlated well using the functional form:

$$W_1 = a + bI_w + cS_w$$

The weight estimating relationship (WER) derived is:

$$W_1 = 0.930\ I_w + 6.44\ S_w + 390 \qquad \text{Medium and Large Aircraft}$$

The actual versus estimated weights for medium and large aircraft are shown in Figure 5.1. The correlation is good except for the C-130 and C-133 wing weights. These two aircraft have a lower design speed and much simpler high-lift devices.

Table 5.1

WING, TAIL, AND BODY SYSTEMS WEIGHT AND DESIGN DATA - COMMERCIAL AIRCRAFT

	Symbol	Citation 500 Series	MDAT 30	MDAT 50	F-28	MDAT 70	DC-9-10
Wing							
Wing System Weight (Lb)	W_1	1,020	3,143	4,360	7,526	5,910	9,366
Takeoff Gross Weight (Lb)	TOGW	11,500	34,480	46,850	62,000	61,000	86,300
Zero Fuel Weight (Lb)	ZFW	8,900	27,450	37,760	47,600	49,450	71,800
Geometry and Design Data:							
Area - Theo. Trap (Ft^2)	S_w	269	342	464	822	605	934
Wing Loading (Lb/Ft^2)	W/S	43	101	101	75	101	92
Aspect Ratio	AR	7.1	9.0	9.0	7.27	9.0	8.6
Taper Ratio	λ	0.39	0.3	0.3	0.361	0.3	0.254
Average Thickness-to-Chord Ratio	t/c	0.123	0.143	0.143	0.129	0.143	0.116
Sweep Angle of Quarter Chord (Deg)	Ω C/4	1.4	4.9	4.9	16.0	4.9	24.0
Ultimate Load Factor	n	6.3	3.75	3.75	5.14	3.75	3.75
Wing Index	I_w	207	500	796	1,656	1,188	2,814
Tail							
Tail System Weight (Lb)	W_2	288	1,010	1,193	1,477	1,505	2,619
Horiz. Tail Including Elevator	W_{2A}	173	405	500	809	645	1,527
Vert. Tail Including Rudder	W_{2B}	115	605	693	668	860	1,092
Geometry Data:							
Horiz. Tail Area-Theo (Ft^2)	S_h	72	112	138	210	177	276
Vert. Tail Area-Theo (Ft^2)	S_v	51	104	119	132	147	161
Body							
Body System Weight (Lb)	W_3	930	4,276	5,692	6,909	7,118	9,452
Design Data:							
No. of Passengers-All Coach	N_p	8	30	50	60	70	80

Table 5.1 (Continued)

WING, TAIL, AND BODY SYSTEMS WEIGHT AND DESIGN DATA - COMMERCIAL AIRCRAFT

	Symbol	BAC-111	DC-9-30	737-200	727-100	727-200	707-320
Wing							
Wing System Weight (Lb)	W_1	9,817	11,391	11,164	17,682	18,529	28,647
Takeoff Gross Weight	TOGW	99,650	108,000	104,000	161,000	175,000	312,000
Zero Fuel Weight (Lb)	ZFW	81,000	87,000	85,000	118,000	140,000	190,000
Geometry and Design Data:							
Area - Theo. Trap (Ft^2)	S_W	1,014	1,001	964	1,520	1,520	2,892
Wing Loading (Lb/Ft^2)	W/S	98	108	108	106	115	108
Aspect Ratio	AR	8.6	8.7	7.8	7.7	7.7	7.3
Taper Ratio	λ	0.333	0.204	0.340	0.372	0.372	0.308
Average Thickness-to-Chord Ratio	t/c	0.112	0.111	0.133	0.123	0.123	0.127
Sweep Angle of Quarter Chord (Deg)	Ω C/4	22.2	24.5	25.0	32.0	32.0	35.0
Ultimate Load Factor	U	3.75	3.75	3.75	3.75	3.75	3.75
Wing Index	I_w	3,512	3,759	2,740	6,192	7,018	14,055
Tail							
Tail System Weight (Lb)	W_2	2,470	2,790	2,777	4,148	4,142	6,004
Horiz. Tail Including Elevator	W_{2A}	1,610	1,635	1,606	1,999	1,921	4,043
Vert. Tail Including Rudder	W_{2B}	860	1,155	1,171	2,149	2,221	1,961
Geometry Data:							
Horiz. Tail Area-Theo (Ft^2)	S_h	258	276	312	377	377	625
Vert. Tail Area-Theo (Ft^2)	S_v	180	161	224	384	384	312
Body							
Body System Weight (Lb)	W_3	11,274	11,118	11,920	17,589	22,415	22,299
Design Data:							
No. of Passengers-All Coach	N_p	99	110	115	138	158	162

Table 5.1 (Continued)

WING, TAIL, AND BODY SYSTEMS WEIGHT AND DESIGN DATA - COMMERCIAL AIRCRAFT

	Symbol	DC-8-55	DC-8-62	DC-10-10	L-1011	DC-10-40	747	SCAT-15
Wing								
Wing System Weight (Lb)	W_1	34,909	36,247	48,990	47,401	57,748	88,741	83,940
Takeoff Gross Weight	TOGW	325,000	335,000	430,000	430,000	565,000	775,000	631,000
Zero Fuel Weight (Lb)	ZFW	224,000	195,000	335,000	325,000	391,000	526,500	364,550
Geometry and Design Data:								
Area - Theo. Trap (Ft^2)	S_w	2,883	2,927	3,550	3,456	3,610	4,960	10,744
Wing Loading (Lb/Ft^2)	W/S	113	114	121	124	157	156	59
Aspect Ratio	AR	7.0	7.5	6.8	6.9	7.2	7.7	1.6
Taper Ratio	λ	0.230	0.200	0.300	0.298	0.273	0.356	0.096
Average Thickness-to-Chord Ratio	t/c	0.111	0.111	0.112	0.108	0.112	0.122	0.029
Sweep Angle of Quarter Chord (Deg)	Ω C/4	30.6	30.6	35.0	35.0	35.0	37.5	0
Ultimate Load Factor	U	3.75	3.75	3.75	3.75	3.75	3.75	3.75
Wing Index	I_w	14,557	15,050	24,600	25,258	33,166	59,172	14,215
Tail								
Tail System Weight (Lb)	W_2	4,952	4,930	9,798*	8,570	10,533*	11,958	8,590
Horiz. Tail Including Elevator	W_{2A}	3,212	3,190	7,593	6,848	8,306	8,017	5,320
Vert. Tail Including Rudder	W_{2B}	1,740	1,740	2,205	1,722	2,227	3,941	3,270
Geometry Data:								
Horiz. Tail Area-Theo (Ft^2)	S_h	559	559	1,338	1,282	1,338	1,470	496
Vert. Tail Area-Theo (Ft^2)	S_v	352	352	287*	550	287*	830	230
Body								
Body System Weight (Lb)	W_3	22,246	23,704	44,790	49,432	46,522	68,452	54,322
Design Data:								
No. of Passengers-All Coach	N_p	165	189	330	330	308	435	234

* DC-10 Upper Vertical Only - Removed the lower vertical tail weight of 3,859 lb. from the DC-10-10 and 3,921 lb. from the DC-10-40.

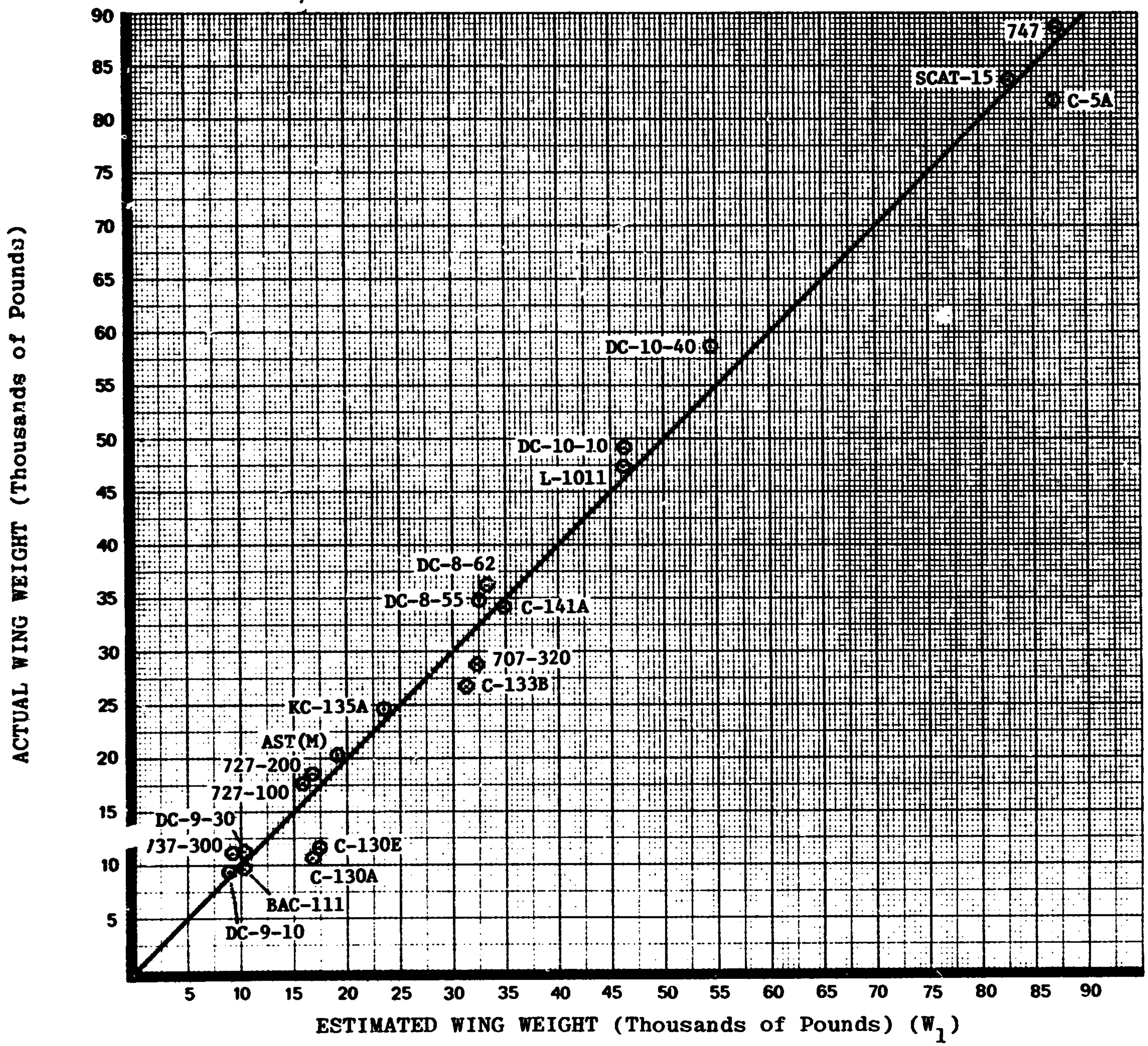
Table 5.2

WING, TAIL, AND BODY SYSTEMS WEIGHT AND DESIGN DATA - MILITARY AIRCRAFT

	Symbol	C-130A	C-130E	KC-135A	C-133B	C-141A	C-5A	AST(M)
Wing								
Wing System Weight (Lb)	W_1	10,593	11,647	24,719	27,064	34,262	81,782	20,560
Takeoff Gross Weight	TOGW	108,000	155,000	275,000	286,000	316,100	728,000	163,500
Zero Fuel Weight (Lb)	ZFW	87,290	107,890	190,380	215,000	204,500	542,800	143,000
Geometry and Design Data:								
Area - Theo. Trap (Ft^2)	S	1,808	1,808	2,453	2,673	3,000	6,200	1,890
Wing Loading (Lb/Ft^2)	W_T/S	60	86	112	107	105	117	87
Aspect Ratio	AR	9.7	9.7	7.0	12.1	8.5	7.7	7.0
Taper Ratio	λ	0.440	0.440	0.331	0.226	0.335	0.338	0.300
Average Thickness-to-Chord Ratio	t/c	0.147	0.147	0.148	0.163	0.121	0.119	0.144
Sweep Angle of Quarter Chord (Deg)	Ω C/4	0	0	35.0	0	25.0	24.5	25.0
Ultimate Load Factor	U	4.5	3.75	3.00	3.75	3.75	3.75	5.11
Wing Index	I_w	5,007	5,550	7,909	14,703	16,232	50,237	6,583
Tail								
Tail System Weight (Lb)	W_2	3,190	3,409	4,958	6,147	5,745	12,344	8,730
Horiz. Tail Including Elevator	W_{2A}	2,106	2,250	3,192	3,721	3,155	6,788	5,127
Vert. Tail Including Rudder	W_{2B}	1,084	1,159	1,766	2,4[illegible]6	2,590	5,556	2,602
Geometry Data:								
Horiz. Tail Area-Theo (Ft^2)	S_h	545	545	500	801	483	966	730
Vert. Tail Area-Theo (Ft^2)	S_v	300	300	312	537	416	961	648
Body								
Body System Weight (Lb)	W_3	14,045	14,241	17,850	32,119	28,578	115,216	29,025
Design Data:								
Fuselage Wetted Area (Ft^2)	S_b	3,339	3,339	4,420	6,900	5,096	16,507	4,563

Figure 5.1

WING ACTUAL vs. ESTIMATED WEIGHTS - MEDIUM AND LARGE AIRCRAFT



For small aircraft (S_w less than about 900 square feet; F-28 and smaller) wing weight was correlated using the functional form:

$$\frac{W_1}{S_w} = a + b\,\frac{I_w}{S_w}$$

The WER derived is:

$$W_1 = 4.24\, I_w + 0.57\, S_w \qquad \text{Small Aircraft}$$

In contrast to medium and large aircraft, I_w is considerably more important than S_w for predicting the weight of small aircraft. This is possibly the result of less sophisticated control surfaces and lighter secondary structure. The actual versus estimated wing weights for small aircraft are shown in Figure 5.2.

Because the calculation to determine the bending material unit weight is rather involved, an alternative wing WER has been derived. This is a function only of the takeoff gross weight. The data are plotted in Figure 5.3. The alternative equation is:

$$W_1 = 0.112\ \text{TOGW} - 1{,}720$$

The SCAT-15 and AST(M) wing weights were not included in the derivation of this equation. It must be cautioned that while the coefficient of correlation is very high, that this WER is valid only for transports which are similar in design to those which were used in the derivation of the WER. This WER is not appropriate for newer designs such as STOL aircraft or some suggested newer aircraft with higher aspect ratio wings which provide greater fuel economy.

Tail:

The total tail area (horizontal and vertical) appears to be a reasonable predictor of tail weight. The tail weight data are plotted against this variable in Figure 5.4. The weight of a "T" tail is higher than the weight of a conventional tail for the same tail area. This is obvious for the vertical portion of a "T" tail must have extra stiffness and strength to transfer the horizontal tail loads into the fuselage. The DC-10 tail

Figure 5.2

WING ACTUAL vs. ESTIMATED WEIGHTS - SMALL AIRCRAFT

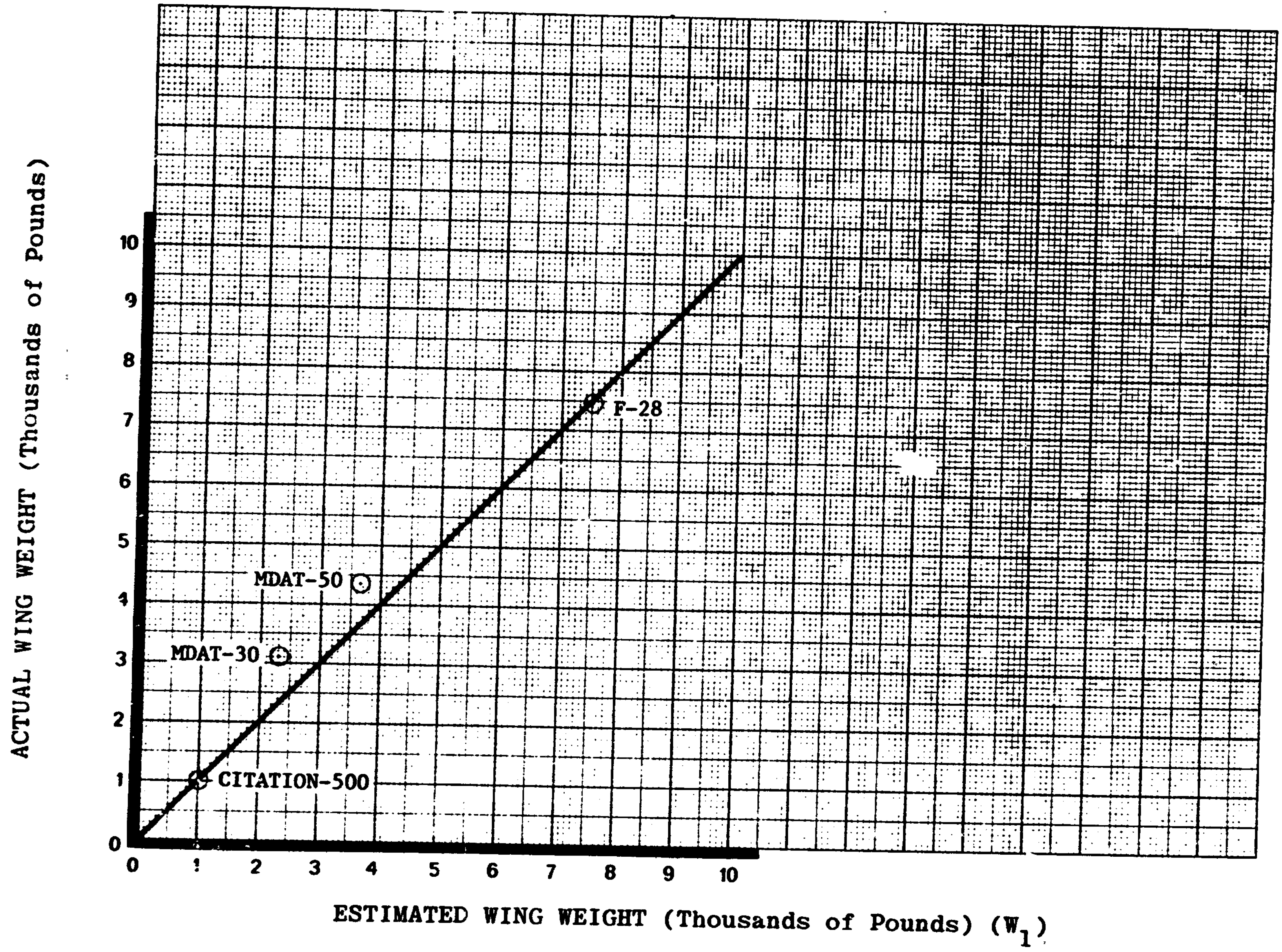


Figure 5.3

WING WER - ALTERNATE EQUATION

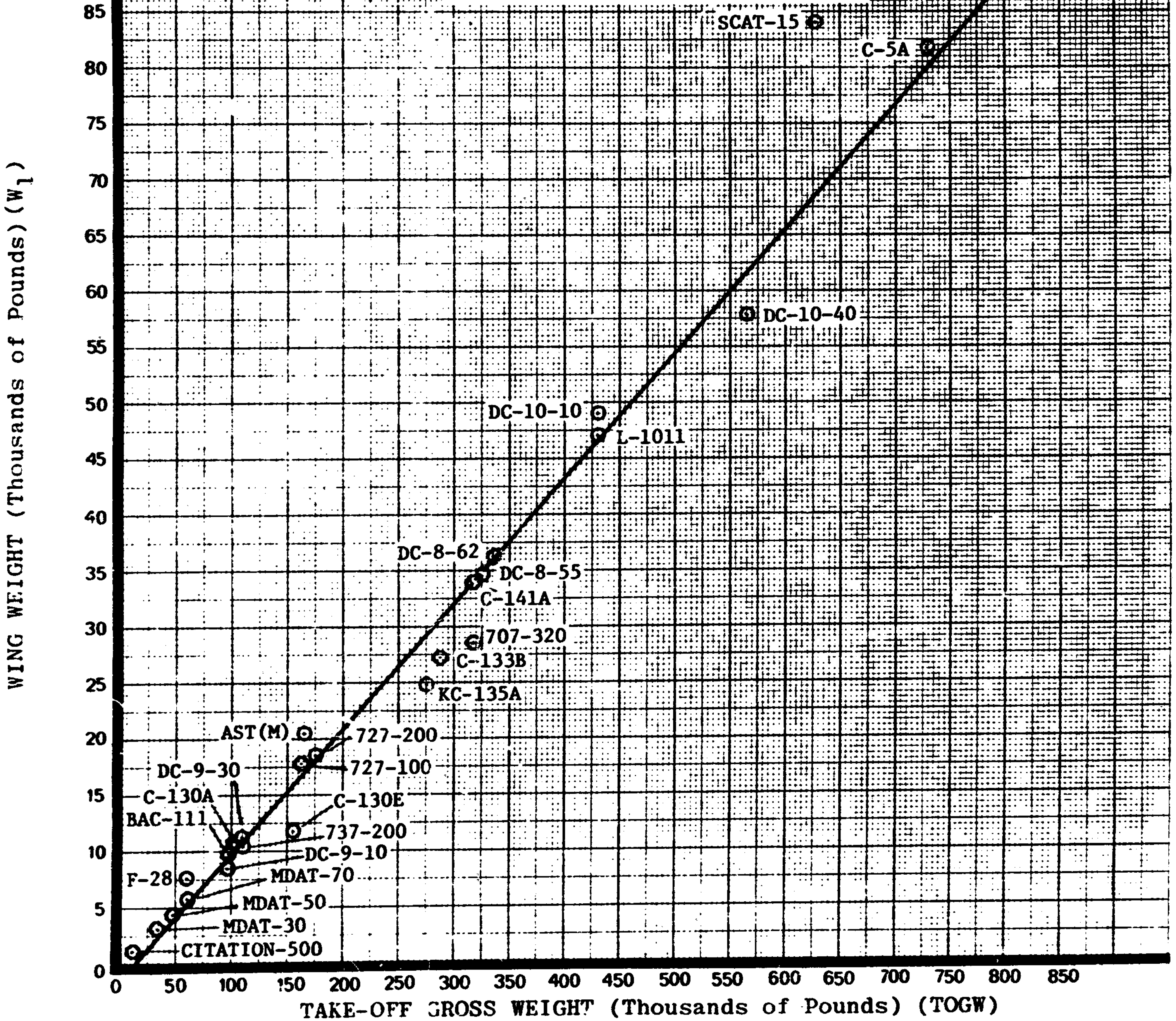
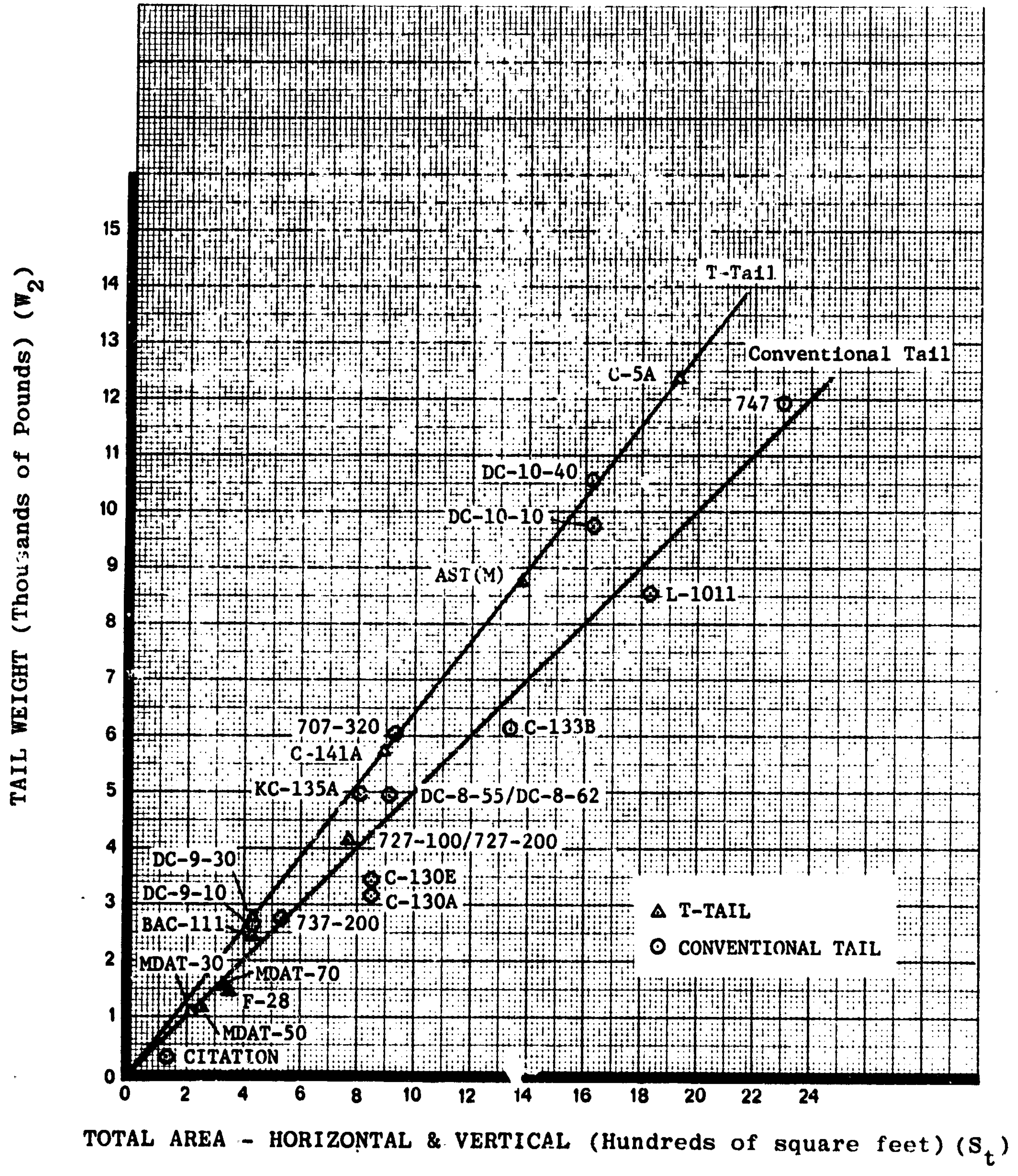


Figure 5.4

TAIL WERs



weight is heavier than might be expected due to the split, double hinged rudder. And, the DC-10-40 is heavier than the DC-10-10 due to its higher tail loads resulting from a higher design gross weight. On the other hand, the C-130 and C-133 have lower tail weights because these aircraft have lower design speeds and tails with lower sweep angles.

Separate WER equations were derived for conventional and for "T" tails. The DC-10 data were not used because of its unique design as mentioned above. The equations are:

$$W_2 = 5.03\ S_t \qquad \text{Conventional Tail}$$

$$W_2 = 6.39\ S_t \qquad \text{"T" Tail}$$

Body:

For the commercial aircraft, body weight correlated well with the number of passengers. This was expected since all of the bodies in the data base have been designed for about the same pressurized loads and have other fairly comparable design requirements. The number of passengers each transport could carry was normalized by assuming all coach seating at a seat pitch of 34 inches. This represents 6 abreast seating for the DC-8 or 707, 9 abreast seating for the DC-10 and L-1011, and 10 abreast seating for the 747. The body weight data are plotted versus the number of passengers in Figure 5.5. Larger aircraft tend to have a higher fuselage weight per passenger. In order to better fit the data, it was decided to derive separate WERs for commercial transports with less than 100 passengers and more than 100 passengers. The equations are:

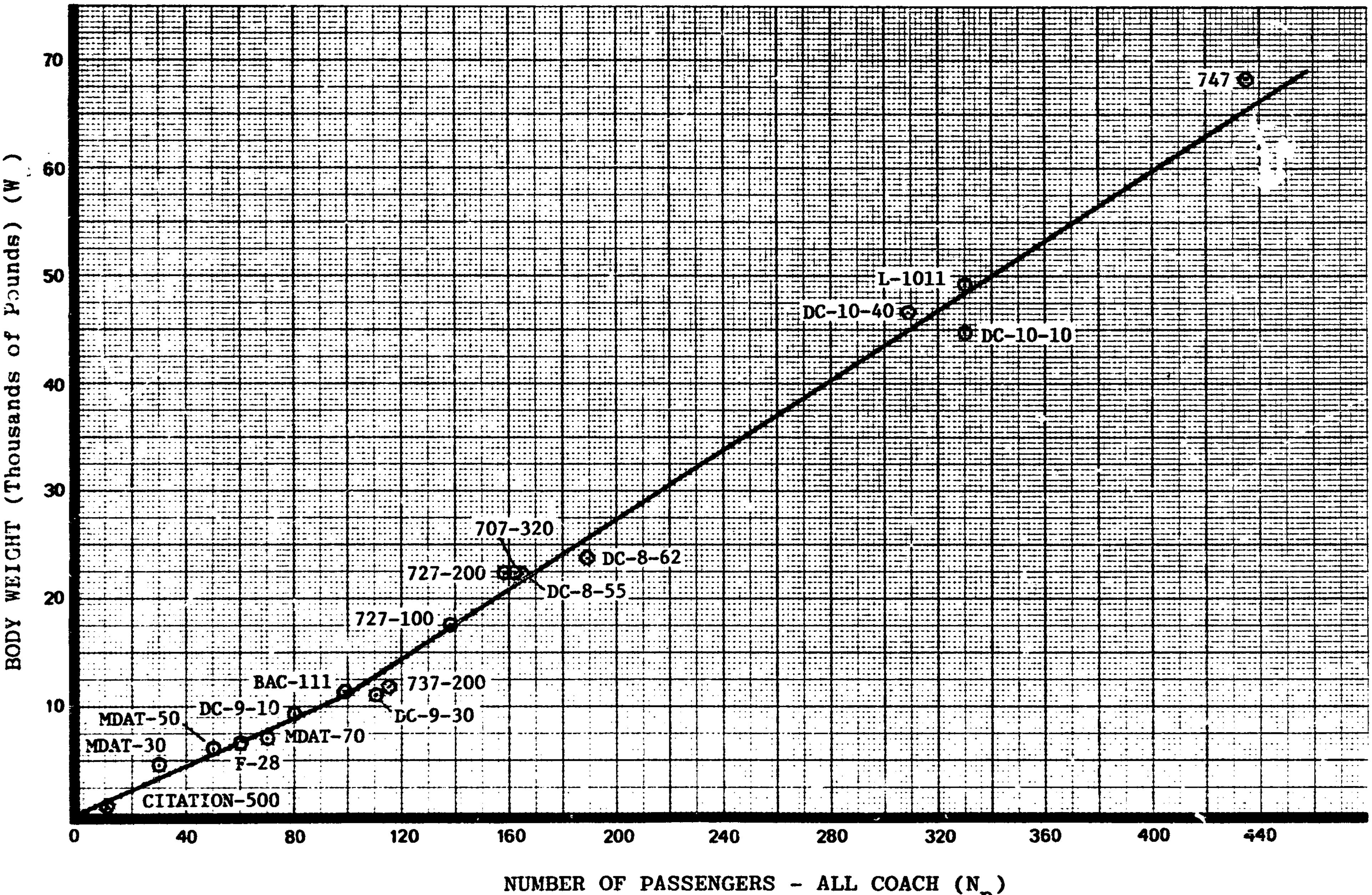
$$W_3 = 161\ N_p - 5,110 \qquad \text{Medium \& Large Aircraft}$$

$$W_3 = 110\ N_p \qquad \text{Small Aircraft}$$

Derivation of the WER for small aircraft excluded the thirty and seventy passenger medium density study airplanes because of the study stretch-shrink ground rules for these two vehicles.

Figure 5.5

BODY WER - COMMERCIAL AIRCRAFT

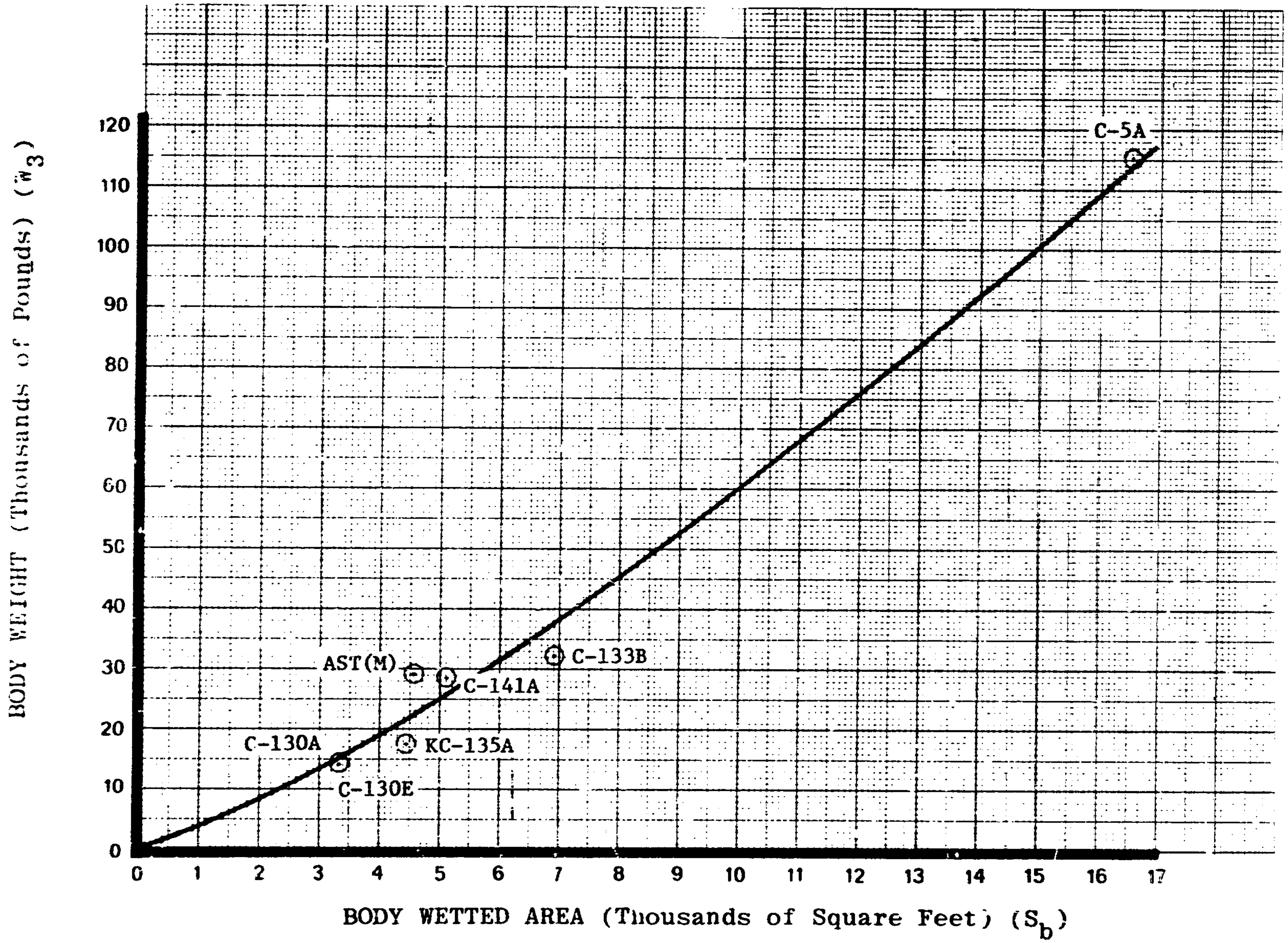


For military aircraft, the body weight correlated well with the body wetted area (S_b). The wetted area is the body wetted area without cutouts and excluding wheel pod fairings. The military body data are plotted in Figure 5.6. There fuselages are all pressurized and are fairly comparable in design. The C-5A weight might appear to be high, but it has a separate upper deck troop compartment, integral cargo loading system, and a visor nose and ramp to permit nose loading in addition to the tail loading capability. The military transport body WER derived is:

$$W_3 = 0.467\ S_b^{1.277} \qquad \text{Military Aircraft}$$

Figure 5.6

BODY WER - MILITARY AIRCRAFT



B. ALIGHTING GEAR SYSTEM

Weight and Design Characteristics

Weight and design characteristics for commercial and military transport aircraft alighting gears are presented in Tables 5.3 and 5.4, respectively. The alighting gear weight is broken out into the same four subsystems for which CERs were derived: structure, controls, wheels and brakes, and tires.

Certain aircraft have special alighting gear features. The C-130E, C-133B, C-5A and AST(M) have low pressure tires; the C-5A has kneeling, crosswind prepositioning, and tire inflation/deflation provisions and the AST(M) has a relatively high sink speed. In developing WERs, the alighting gear system weights of these aircraft were adjusted to exclude these special features. A description of these weight adjustments is presented in Table 5.5. The low-to-high-pressure tire weight adjustments are derived from parametric relations descriptive of each type of tire. The adjustments for the special C-5A features are based on detailed weight statements. The sink speed adjustment for the AST(M) is based on trade study data.[17]

Weight Estimating Relationships

WERs for the complete alighting gear system were developed separately for medium and large commercial aircraft, small commercial aircraft and military aircraft. Data for medium and large commercial and military aircraft are plotted in Figure 5.7. Commercial transport alighting gears are wing mounted whereas military transport alighting gears are fuselage mounted. For the same takeoff gross weight, the wing mounted commercial gears are heavier than the fuselage mounted military gears because the wing mounted struts are usually longer and because wing attach bulkheads and loadpath material to the fuselage are required for wing mounted gears. Fuselage attach bulkheads for both wing and fuselage mounted gear are included with body. Therefore, separate WERs were developed for commercial and military aircraft. As can be seen in Figure 5.7, the weight data correlated well with the takeoff gross weight.

Table 5.3

ALIGHTING GEAR SYSTEM WEIGHT AND DESIGN DATA - COMMERCIAL AIRCRAFT

	Symbol	Citation 500 Series	MDAT-30	MDAT-50	F-28	MDAT-70	DC-9-10	BAC-111	DC-9-30
Weight Data									
Alighting Gear	W_4	425	1,379	1,874	2,564	2,44[illegible]	3,640	3,465	4,182
Structure	W_{4A}	—	—	—	1,340	—	—	—	1,943
Controls	W_{4B}	—	—	—	208	—	—	—	534
Wheels and Brakes*	W_{4C}	—	—	—	633	—	—	—	1,130
Tires	W_{4D}	—	—	—	383	—	—	—	575
%Nose/Main		20/80	14.3/85.7	14.3/85.7	14.3/85.7	14.3/85.7	12.2/87.8	14.8/85.2	11.3/88.7
%MEW		6.7	6.7	7.0	7.7	7.1	7.6	6.7	7.5
Take-off Gross Weight	TOGW	11,500	34,480	46,850	62,000	61,000	86,300	99,650	108,000
Design Data									
No. of Nose Gear Struts	N_s	1	1	1	1	1	1	1	1
No. of Main Gear Struts	N_s	2	2	2	2	2	2	2	2
Sink Speed (fps)		10	10	10	10	10	10	—	10
Kneeling		No	No	No	No	No	No	No	No
Carbon Brakes		No	No	No	No	No	No	No	No
Tire Pressure		High	High	High	High	High	High	High	High

* Includes Air.

Table 5.3 (Continued)

ALIGHTING GEAR SYSTEM WEIGHT AND DESIGN DATA - COMMERCIAL AIRCRAFT

	Symbol	737-200	727-100	727-200	707-320	DC-8-55	DC-8-62	DC-10-10	DC-10-30	747	SCAT-51
Weight Data											
Alighting Gear	W_4	4,038	7,244	7,948	11,216	11,682	11,449	18,581	25,085	32,220	28,720
Structure	W_{4A}	—	3,327	—	5,864	—	5,965	10,367	—	17,885	—
Controls	W_{4B}	—	880	—	1,193	—	965	1,491	—	4,141	—
Wheels and Brakes*	W_{4C}	—	2,008	—	4,159	—	2,971	4,548	—	7,201	—
Tires	W_{4D}	—	1,029	—		—	1,548	2,175	—	2,993	—
%Nose/Main		11.9/88.1	16.1/83.9	14.6/85.4	8/92	8.6/91.4	8.8/91.2	7.9/92.1	7.3/92.7	9.4/90.6	9.5/90.5
%MEW		7.2	8.7	8.3	9.1	8.9	8.5	8.3	10.2	10.1	9.5
Take-off Gross Weight	TOGW	104,000	161,000	175,000	312,000	325,000	335,000	430,000	555,000	775,000	631,000
Design Data											
No. of Nose Gear Struts	N_s	1	1	1	1	1	1	1	1	1	1
No. of Main Gear Struts	N_s	2	2	2	2	2	2	2	3	4	2
Sink Speed (fps)		10	10	10	10	10	10	10	10	10	10
Kneeling		No	No	No	No	No	No	No	No	No	No
Carbon Brakes		No	No	No	No	No	No	No	No	No	No
Tire Pressure		High	High	High	High	High	High	High	High	High	High

* Includes Air.

Table 5.4

ALIGHTING GEAR SYSTEM WEIGHT AND DESIGN DATA - MILITARY AIRCRAFT

	Symbol	C-130E	KC-135A	C-133B	C-141A	C-5A	AST(M)
Weight Data							
Alighting Gear	W_4	5,077	10,698	11,062	10,529	37,628	9,360
Structure		1,826	5,797	—	5,229	25,768	—
Controls		957	1,144	—	1,208	1,771	—
Wheels and Brakes*		1,177	}3,757	—	}4,092	5,956	—
Tires		1,117		—		4,133	
%Nose/Main		14.9/85.1	8.5/91.5	13.3/86.7	11.8/88.2	11.6/88.4	16.7/83.3
%MEW		7.4	11.5	9.2	7.9	11.8	5.7
Take-off Gross Weight	TOGW	155,000	275,000	286,000	316,100	728,000	163,500
Design Data							
No. of Nose Gear Struts	N_3	1	1	1	1	1	1
No. of Main Gear Struts	N_s	4	2	4	2	4	2
Sink Speed (fps)		9	9	9	10	10	20.5
Kneeling		No	No	No	No	Yes	No
Carbon Brakes		No	No	No	No	No	No
Tire Pressure		Low	High	Low	High	Low	Low

* Includes Air.

Table 5.5

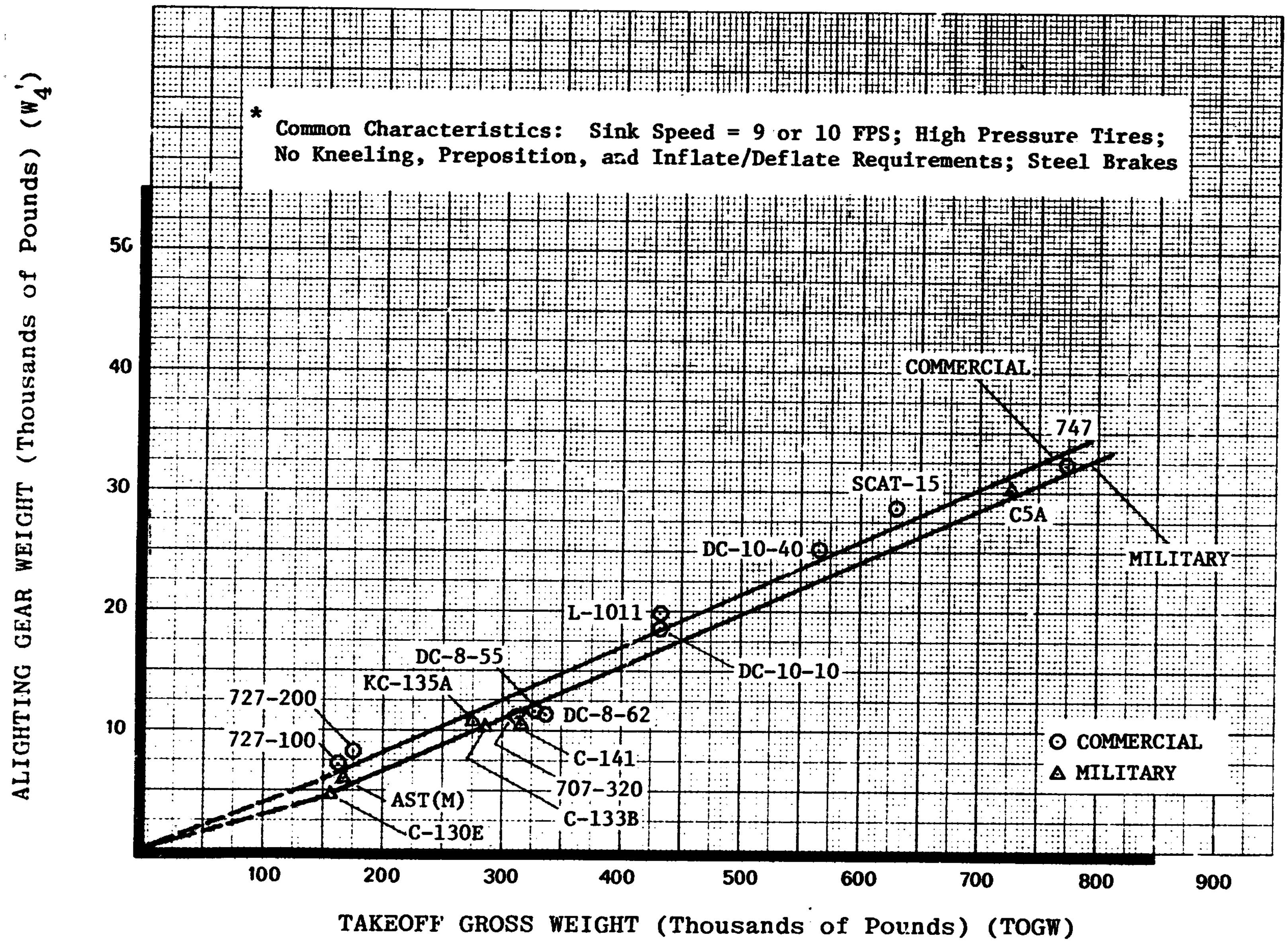
ALIGHTING GEAR WEIGHT ADJUSTMENTS

The alighting gear weights of the aircraft listed below were adjusted as shown for correlation purposes in order to remove the weight effects of special design requirements. No adjustments were made to the other aircraft.

	Lbs/Airplane
C-130E	
Group Weight Statement Weight	5,077
Low to High Pressure Tires	- 500
Adjusted Alighting Gear System Weight	4,577
C-133B	
Group Weight Statement Weight	11,062
Low to High Pressure Tires	- 946
Adjusted Alighting Gear System Weight	10,116
C-5A	
Group Weight Statement Weight	37,628
Low to High Pressure Tires	- 1,583
Removed weight increment resulting from kneeling, preposition, and inflate/deflate requirements	- 5,836
Adjusted Alighting Gear System Weight	30,209
AST(M)	
Group Weight Statement Weight	9,360
Low to High Pressure Tires	- 641
Reduced sink speed requirements from 20.5 ft/sec. to 10 ft/sec.	- 2,700
Adjusted Alighting Gear System Weight	6,019

Figure 5.7

ALIGHTING GEAR WER*—MEDIUM AND LARGE AIRCRAFT



The equations are:

$$W_4' = 0.0440\ (TOGW) - 672 \qquad \text{Medium and Large Commercial}$$

$$W_4' = 0.0439\ (TOGW) - 2{,}050 \qquad \text{Medium and Large Military}$$

The data for small transports, all of which are commercial, are plotted in Figure 5.8. The equation derived is:

$$W_4' = 0.0395\ (TOGW) \qquad \text{Small}^{*}$$

The "prime"(') on W_4 indicates that these are equations for the basic alighting gear and do not include special features which are discussed below.

Alighting gear WERs for each of the four subsystems were developed by plotting the percent of total alighting gear weight for each subsystem as a function of takeoff gross weight as shown in Figures 5.9 to 5.12. The equations are:

$$W_{4A} = W_4' \left[0.450 + 23.1 \times 10^{-8}\ (TOGW)\right] \qquad \text{Structure}$$

$$W_{4B} = W_4' \left[0.130 - 6.56 \times 10^{-8}\ (TOGW)\right] \qquad \text{Controls}$$

$$W_{4C} = W_4' \left[0.268 - 8.12 \times 10^{-8}\ (TOGW)\right] \qquad \text{Wheels and Brakes}$$

$$W_{4D} = W_4' \left[0.152 - 8.38 \times 10^{-8}\ (TOGW)\right] \qquad \text{Tires}$$

Adjustments are required to the weights estimated with the WERs developed above if there are special design features. These special design features include: low pressure tires; high sink speed; and provisions for special kneeling, crosswind prepositioning, tire inflation/deflation; and carbon brakes in place of steel brakes. Adjustments to the alighting gear weight for these features are shown in percentage terms in Figure 5.13. The data used in developing the percentages are from Tables 5.3, 5.4 and 5.5. These

* Data for small military transports, which are not contained in this report, indicate that: $W_4' = 0.0302\ (TOGW)$.

Figure 5.8

ALIGHTING GEAR WER - SMALL AIRCRAFT

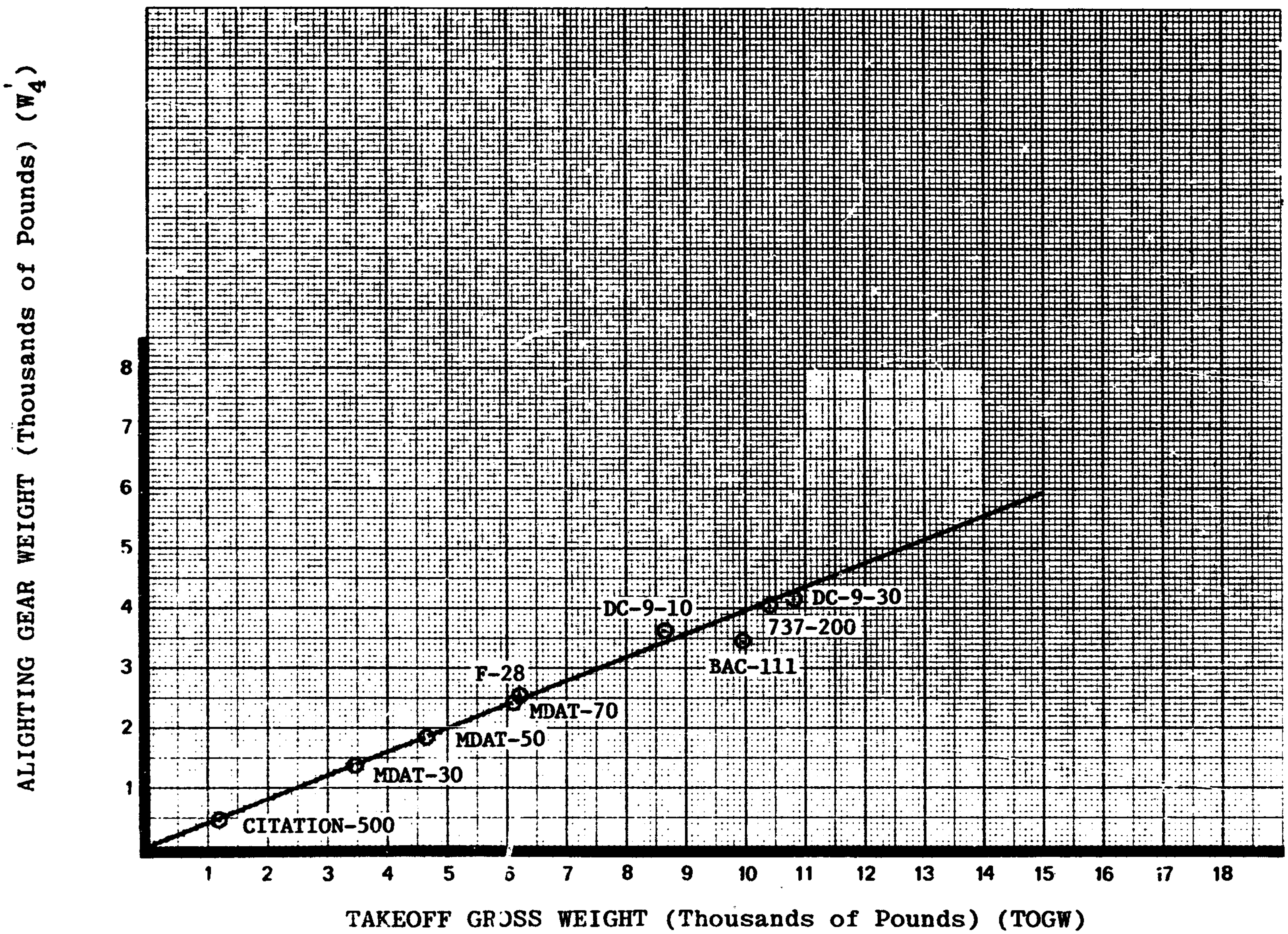


Figure 5.9

ALIGHTING GEAR STRUCTURE WER

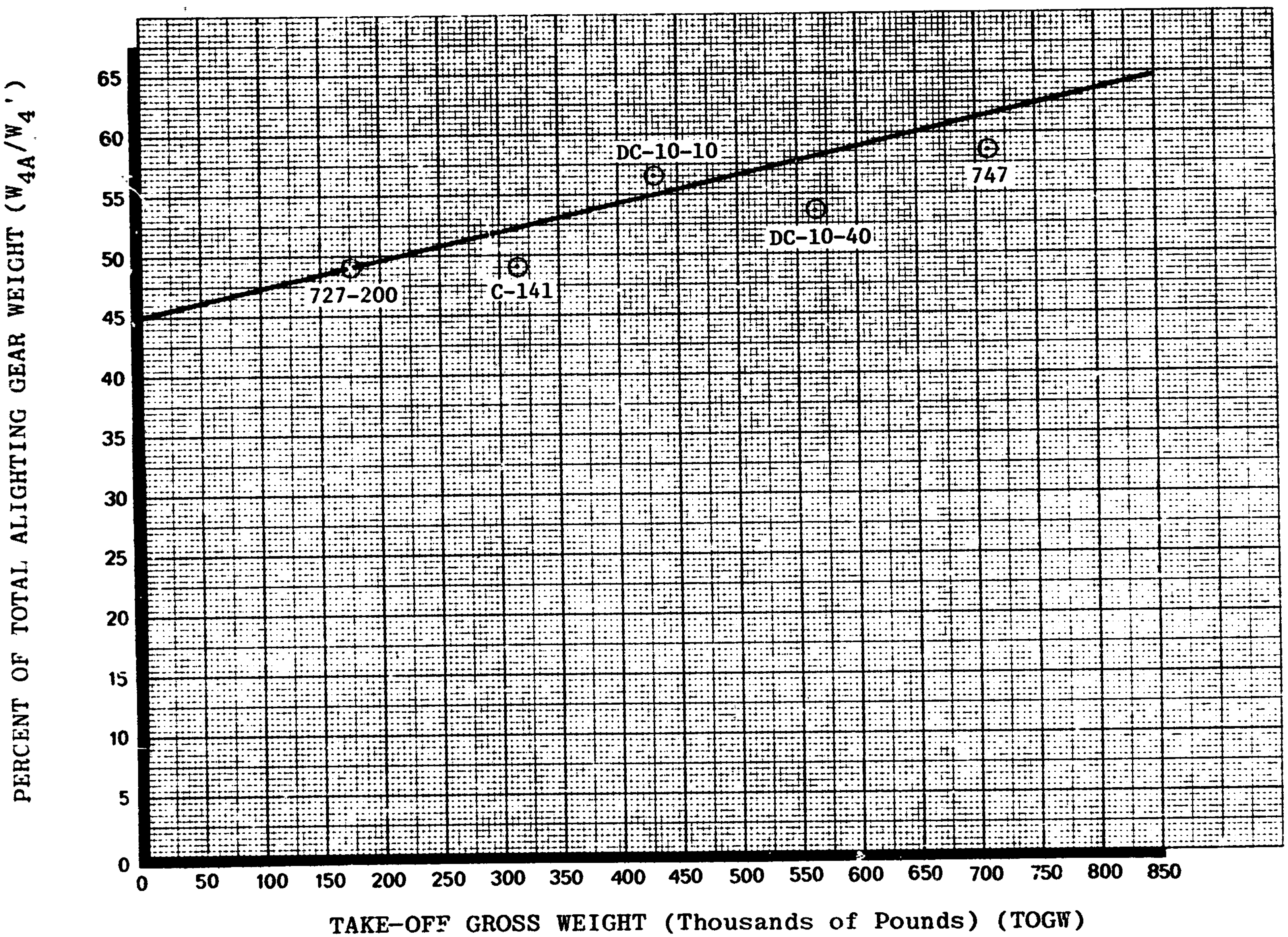


Figure 5.10

ALIGHTING GEAR CONTROLS WER

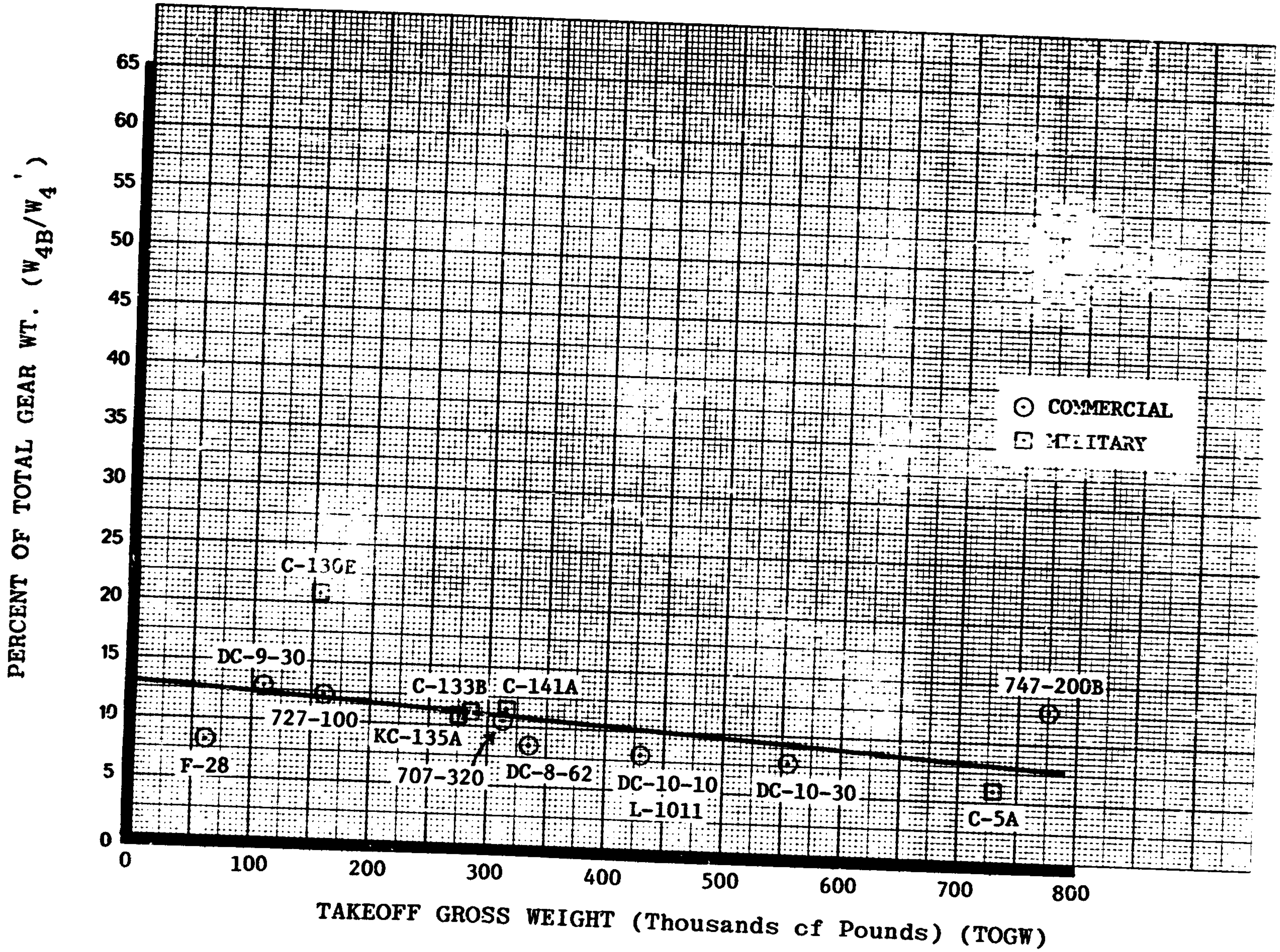


Figure 5.11

WHEELS AND BRAKES WER

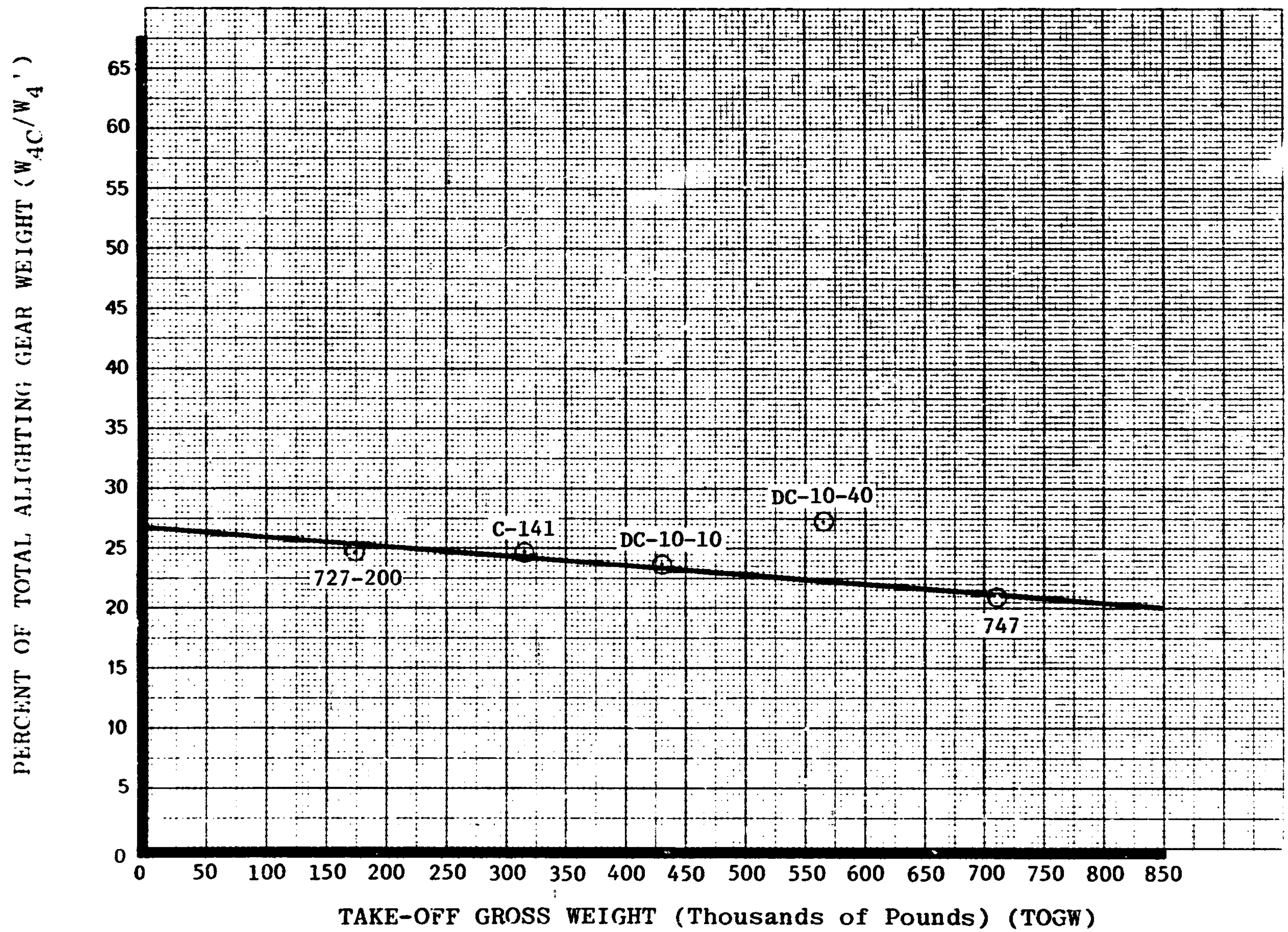


Figure 5.12

TIRE WER

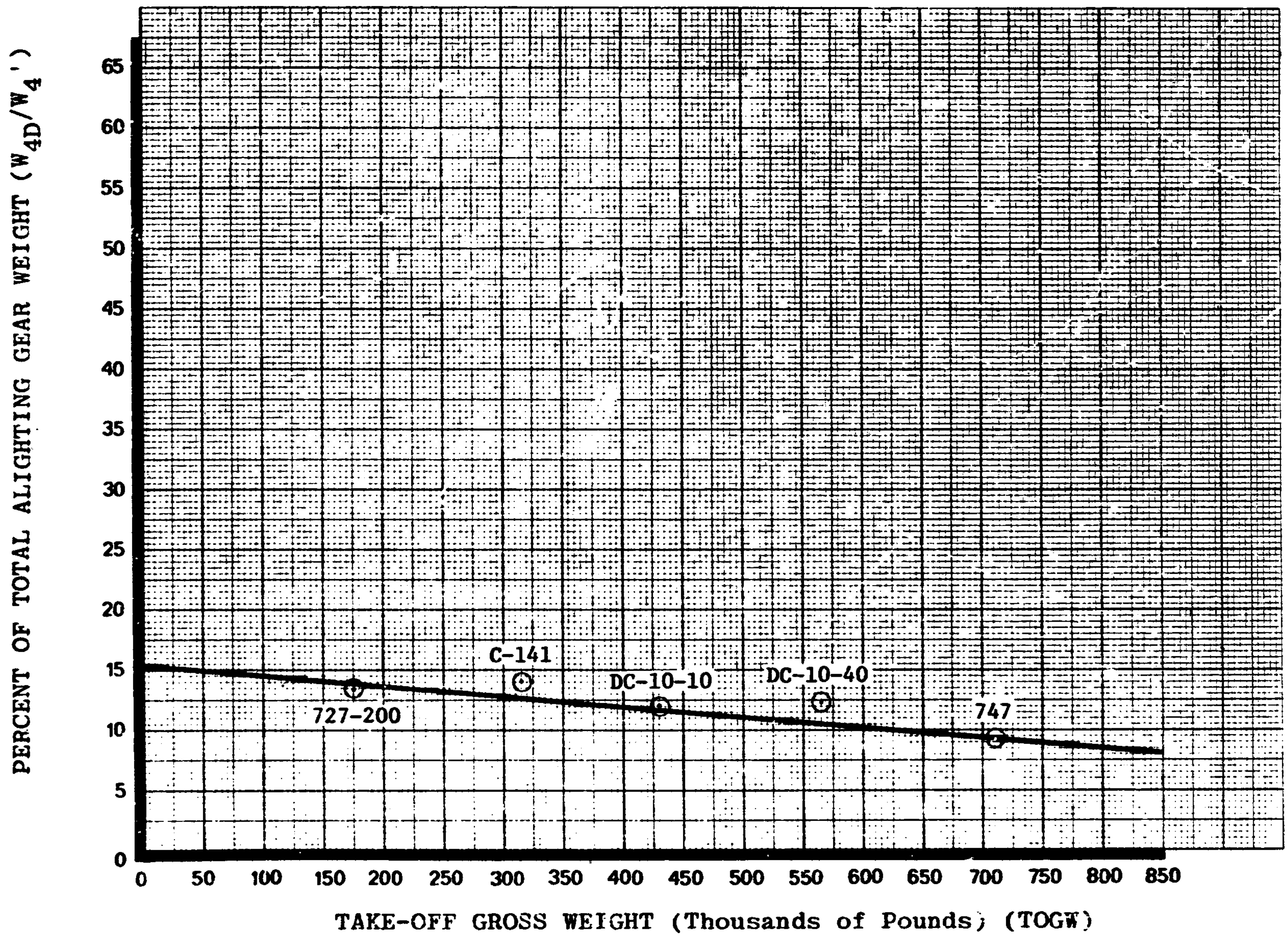
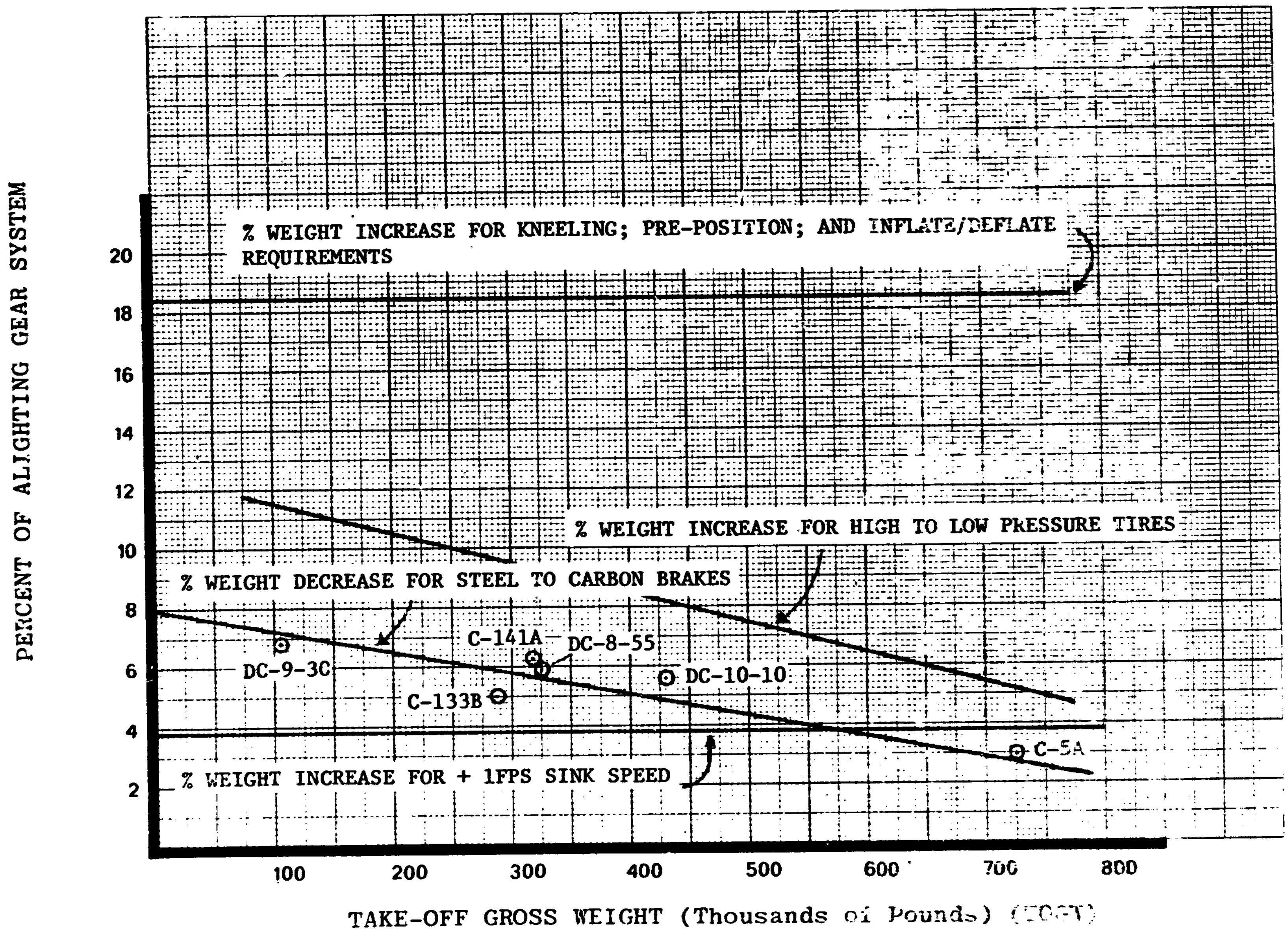


Figure 5.13

ADJUSTMENTS FOR SPECIAL ALIGHTING GEAR DESIGN FEATURES



special features all increase the weight of the alighting gear system except for the use of carbon brakes which decreases the weight. The equations are as follows:

Add for Low Pressure Tires

$$W_{4E} = W_4' \left[0.125 - 0.0102 \times 10^{-5} (TOGW)\right]$$

Add for Each Foot per Second Increase in Sink Speed

$$W_{4F} = 0.038\, W_4'$$

Add for Kneeling Pre-positioning and Inflate/Deflate Requirements

$$W_{4G} = 0.184\, W_4'$$

Subtract for Carbon Brakes

$$W_{4H} = W_4' \left[0.0786 - 0.071 \times 10^{-6} (TOGW)\right]$$

C. NACELLE SYSTEM

Weight and Design Characteristics

Weight and design characteristics for nacelles are presented in Tables 5.6 and 5.7 for commercial and military transport aircraft, respectively. The data base includes aircraft with wing, fuselage and tail mounted engines. The blanks in the table indicate that detailed data were not available for those aircraft. Some additional data were available for sound-treated nacelle designs from the NASA Short Haul Study, and these data are presented in Table 5.8.[18]

Weight Estimating Relationships

Separate WERs were developed for the nacelle cowl and pylon. These WERs must be adjusted for special design features such as an "S" Duct tail mounted nacelle and sound suppression treatment.

Cowl:

At the outset of the study, it was expected that a correlation of cowl weight to engine thrust would be possible. However, the scatter of the data obtained by this relationship was too large to be of use in conceptual design studies. This scatter is apparent in Figure 5.14 where these data are plotted. Such differences as engine dimensions (i.e., CF6 vs. JT9D), inlet dimensions (i.e., DC-8 vs. C-141), fan exhaust duct configuration (i.e., JT8D), fan duct length, and by-pass ratio appear to make a general correlation of cowl weight to thrust impractical.

A cowl weight to frontal area relationship was then examined, but pure area itself produced significant scatter due to the increase of inlet and fan exhaust duct unit weights with size. It was felt that cowl weight might be related to a weighted area index. The weighted area index or cowl weight index was developed as discussed below.

Because of the wide variation of cowl designs, the cowling structure should be divided into several segments. As shown in the diagrams for short duct and long duct nacelles in Figure 5.15 the segments include: 1) the inlet from the lip to the engine front face (L_1), 2) the fan cowl

Table 5.6

NACELLE SYSTEM WEIGHT AND DESIGN DATA - COMMERCIAL AIRCRAFT

	Symbol	Citation JT15D-1	MDAT 30 —	MDAT 50 —	MDAT 70 —	DC-9-10 JT8D-5	BAC 111 MK.512-14DW	DC-9-30 JT8D-9	727-200 JT8D-7	727-100 JT8D-7 Body	727-100 JT8D-7 Tail	727-200 JT8D-9 Body	727-200 JT8D-9 Tail
Weight Data													
Nacelle System Weight (lb)	W_5	241	948	1,294	1,684	1,462	1,191	1,462	1,515	1,241	985	1,231	994
Cowl	W_{5A}	110	508	694	898	682	699	682	897	666	881	656	891
Pylon	W_{5B}	131	440	600	786	780	492	780	618	575	104	575	103
%MEW		3.8	4.6	4.8	4.9	3.0	2.3	2.6	2.6	1.5	1.2	1.3	1.0
Demountable Power Plant (Lb/Eng)	W_{dem}	629	1,891	2,570	3,344	2,918	3,672	3,945	4,143	4,151	4,634	4,201	4,703
Design Data													
Engine Location		Body	Body	Body	Body	Body	Body	Body	Wing	Body	Tail	Body	Tail
Bypass Ratio	BPR	3.3:1	6:1	6:1	6:1	1.1:1	—	1.03:1	1.1:1	1.1:1	1.1:1	1.03:1	1.03:1
Engine Thrust (lb/eng)*	T	2,200	6,450	8,770	11,420	12,250	12,55[illegible]	14,500	14,000	14,000	14,000	14,500	14,500
Cowl Characteristics													
Fan Diameter (in)	D_f	21.0	44.7	52.1	59.4	42.0	—	42.0	—	—	—	—	—
Engine length (in)	L_e	59.3	57.3	66.9	76.3	122.0	—	122.0	—	—	—	—	—
Core length (in)	L_c	—	—	—	—	—	—	—	—	—	—	—	—
Inlet Ratio	L_i/D_f	0.67	0.68	0.68	0.68	0.67	—	0.67	—	—	—	—	—
Fan Ratio	L_f/D_f	3.40	0.45	0.45	0.45	2.86	—	2.86	—	—	—	—	—
Fan Exhaust Ratio	L_{fex}/D_f	—	0.54	0.54	0.54	—	—	—	—	—	—	—	—
Fan Translating Structure Ratio	L_{ftr}/D_f	—	0.32	0.32	0.32	—	—	—	—	—	—	—	—
Average Core Cowl Ratio	$\overline{D}_c/D_f$	—	—	—	—	—	—	—	—	—	—	—	—
Cowl Weight Index	I_c	1,967	5,785	8,236	11,189	7,220	—	7,220	—	—	—	—	—
Pylon Characteristics													
Length (in)	L_{py}	11	24	28	32	23	—	23	—	—	—	—	—
Height (in)	H_{py}	6.0	7.0	8.5	9.8	11.0	—	11.0	—	—	—	—	—
Area (ft^2)	S_{py}	7.8	19.1	22.3	25.5	28.5	—	28.5	—	—	—	—	—
Pylon Weight Index	I_{py}	148	339	380	428	287	—	290	—	—	—	—	—

* Sea level Standard Conditions and Uninstalled.

Table 5.6 (Continued)

NACELLE SYSTEM WEIGHT AND DESIGN DATA - COMMERCIAL AIRCRAFT

	Symbol	707-320 JT4A-5	DC-8-55 JT8D-3B	DC-8-62 JT8D-3B	DC-10-10 CF6-6D Wing	DC-10-10 CF6-6D Tail	L-1011 RB211-22B Wing	L-1011 RB211-22B Tail	DC-10-40 JT9D-15 Wing	DC-10-40 JT9D-15 Tail	747 JT9D-7	SCAT GE4/JSD
Weight Data												
Nacelle System Weight (lb)	W_5	3,176	4,644	6,648	5,675	2,818	5,399	3,517	6,282	3,046	10,830	15,650
Cowl	W_{5A}	1,297	1,924	2,908	2,248	1,732	1,521	2,394	2,226	2,026	5,200	12,720
Pylon	W_{5B}	1,879	2,720	3,740	3,427	1,086	3,878	1,123	4,056	1,020	5,630	2,930
ZMEW		2.5	3.5	4.9	2.5	1.2	2.4	1.5	2.5	1.2	3.2	5.2
Demountable Power Plant (Lb/Eng)	W_{dem}	6,073	6,403	6,449	10,996	11,779	13,769	15,373	13,339	13,500	—	14,880
Design Data												
Engine Location		Wing	Wing	Wing	Wing	Tail	Wing	Tail	Wing	Tail	Wing	Wing
Bypass Ratio	BPR	--	1.3:1	1.3:1	5.9:1	5.9:1	5:1	5:1	4.9:1	4.9:1	4.9.1	0
Engine Thrust (lb/eng)*	T	18,000	18,000	18,000	40,000	40,000	42,000	42,000	45,500	45,500	45,500	51,500
Cowl Characteristics												
Fan Diameter (in)	D_f	--	53.0	53.0	93.0	93.0	--	--	95.6	95.6	95.6	69.6
Engine length (in)	L_e	--	129.0	129.0	175.0	175.0	--	--	128.0	128.0	128.0	143.0
Core length (in)	L_c	--	45.0	--	67.0	67.0	--	--	13.0	13.0	59.0	143.0
Inlet Ratio	L_i/D_f	--	0.86	0.65	0.63	3.25	--	--	0.74	3.35	0.50	2.47
Fan Ratio	L_f/D_f	--	0.48	0.48	0.51	0.51	--	--	0.35	0.35	0.35	—
Fan Exhaust Ratio	L_{fex}/D_f	--	0.45	1.96	0.15	0.15	--	--	0.21	0.21	0.11	—
Fan Translating Structure Ratio	L_{ftr}/D_f	--	0.66	—	0.49	0.49	--	--	0.65	0.65	0.26	—
Average Core Cowl Ratio	$\bar{D}_c/D_f$	--	1.02	—	0.70	0.70	--	--	0.73	0.73	0.70	1.24
Cowl Weight Index	I_c	--	11,500	17,765	26,280	82,440	--	--	27,110	86,770	21,775	38,495
Pylon Characteristics												
Length (in)	L_{py}	105.0	106.0	122.0	124.0	105.0	--	--	130.0	94.0	—	—
Height (in)	H_{py}	30	37	24	35.0	32.0	--	--	35.0	32.0	—	—
Area (ft^2)	S_{py}	34.4	51.6	47.3	62.5	67.5	--	--	62.5	60.4	—	—
Pylon Weight Index	I_{py}	618	354	695	623	573	--	--	793	657	—	—

* Sea level Standard Conditions and Uninstalled.

Table 5.7

NACELLE SYSTEM WEIGHT AND DESIGN DATA - MILITARY AIRCRAFT

	Symbol	KC-135A J57-P-43	C-141A TF33-P-7	C-5A TF39	AST(M) GE13
Weight Data					
Nacelle System Weight (lb)	W_5	2,547	5,630	8,472	4,711
Cowl	W_{5A}	960	3,352	3,352	2,285
Pylon	W_{5B}	1,587	2,278	5,120	2,426
% MEW		2.7	4.3	2.6	4.1
Demountable Power Plant (Lb/Eng)	W_{dem}	4,972	6,455	9,249	4,875
Design Data					
Engine Location		Wing	Wing	Wing	Wing
Bypass Ratio	BPR	—	1.2:1	8:1	6.2:1
Engine Thrust (lb/eng)*	T	13,750	21,000	41,000	19,620
Cowl Characteristics					
Fan Diameter (in)	D_f	—	53.0	96.0	725
Engine length (in)	L_e	—	129.0	181.0	93.0
Core length (in)	L_c	—	—	118.0	—
Inlet Ratio	L_i/D_f	—	0.23	0.43	0.76
Fan Ratio	L_f/D_f	—	0.45	0.33	0.54
Fan Exhaust Ratio	L_{fex}/D_f	—	2.01	—	0.32
Fan Translating Structure Ratio	L_{ftr}/D_f	—	—	0.41	0.43
Average Core Cowl Ratio	$\overline{D}_c/D_f$	—	—	0.64	—
Cowl Weight Index	I_c	—	15,695	20,260	16,200
Pylon Characteristics					
Length (in)	L_{py}	110.0	79.0	86.0	120.0
Height (in)	H_{py}	34.0	38.0	65.0	27.0
Area (ft^2)	S_{py}	36.0	52.0	139.0	35.5
Pylon Weight Index	I_{py}	448	258	88	810

* Sea level Standard Conditions and Uninstalled.

Table 5.8

NACELLE SYSTEM WEIGHT AND DESIGN DATA - NASA SHORT HAUL STUDY AIRCRAFT

	Symbol	1	2	3	4	5	6
Weight Data							
Nacelle System Weight (lb)	W_5	4,062	5,282	4,239	6,359	4,144	7,556
Cowl	W_{5A}	2,294	2,938	2,655	3,747	2,512	4,168
Pylon	W_{5B}	1,768	1,940	1,584	1,832	1,632	1,944
% MEW		4.2	5.3	4.3	6.2	4.2	7.0
Demountable Power Plant (Lb/Eng)	W_{dem}	3,083	3,282	3,352	3,679	3,436	3,980
Design Data							
Engine Location		Wing	Wing	Wing	Wing	Wing	Wing
Bypass Ratio	BPR	6:1	6:1	13.7:1	13.7:1	17.7:1	17.7:1
Engine Thrust (lb/eng)*	T	16,000	16,000	16,000	16,000	16,000	16,000
Cowl Characteristics							
Fan Diameter (in)	D_f	56.5	56.5	66.5	66.5	70.0	70.0
Engine length (in)	L_e	85.0	85.0	93.0	93.0	95.0	95.0
Core length (in)	L_c	--	--	17.0	--	10.5	--
Inlet Ratio	L_i/D_f	0.78	1.00	0.80	0.80	0.66	0.95
Fan Ratio	L_f/D_f	0.45	0.45	0.57	0.57	0.64	0.64
Fan Exhaust Ratio	L_{fex}/D_f	0.38	0.59	0.20	0.68	0.21	0.56
Fan Translating Structure Ratio	L_{ftr}/D_f	0.67	0.67	0.38	0.26	0.36	0.25
Average Core Cowl Ratio	$\overline{D}_c/D_f$	--	--	0.71	--	0.60	--
Cowl Weight Index	I_c	9,375	12,400	13,205	17,885	13,390	21,905
Pylon Characteristics							
Length (in)	L_{py}	103.0	113.0	93.0	116.0	96.0	120.0
Height (in)	H_{py}	17.0	17.0	25.0	25.0	25.0	25.0
Area (ft^2)	S_{py}	21.9	22.0	28.3	28.2	29.1	29.4
Pylon Weight Index	I_{py}	895	995	442	605	453	650

*Sea level Standard Conditions and Uninstalled.

Figure 5.14

COWL WEIGHT vs. ENGINE THRUST

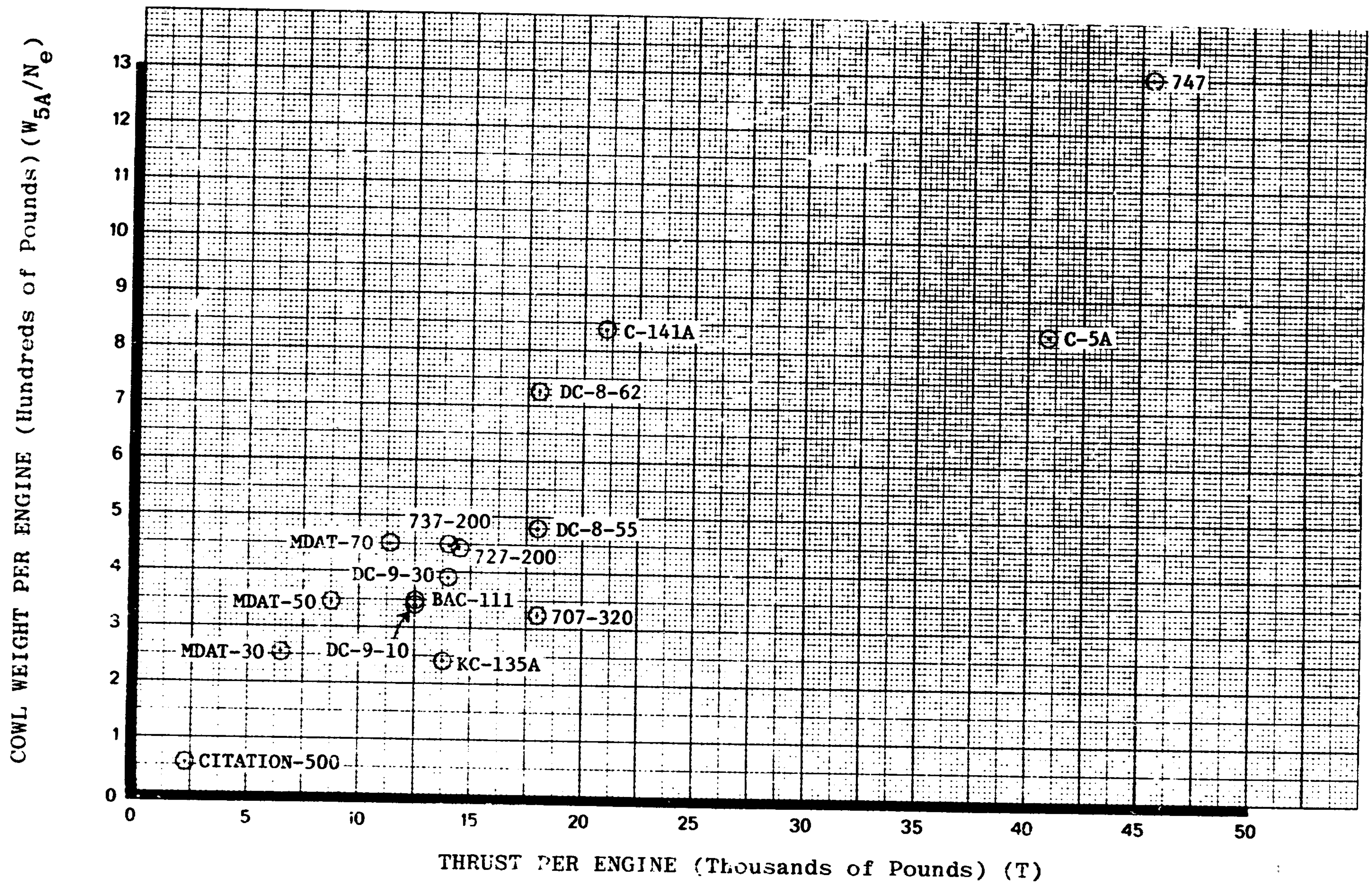
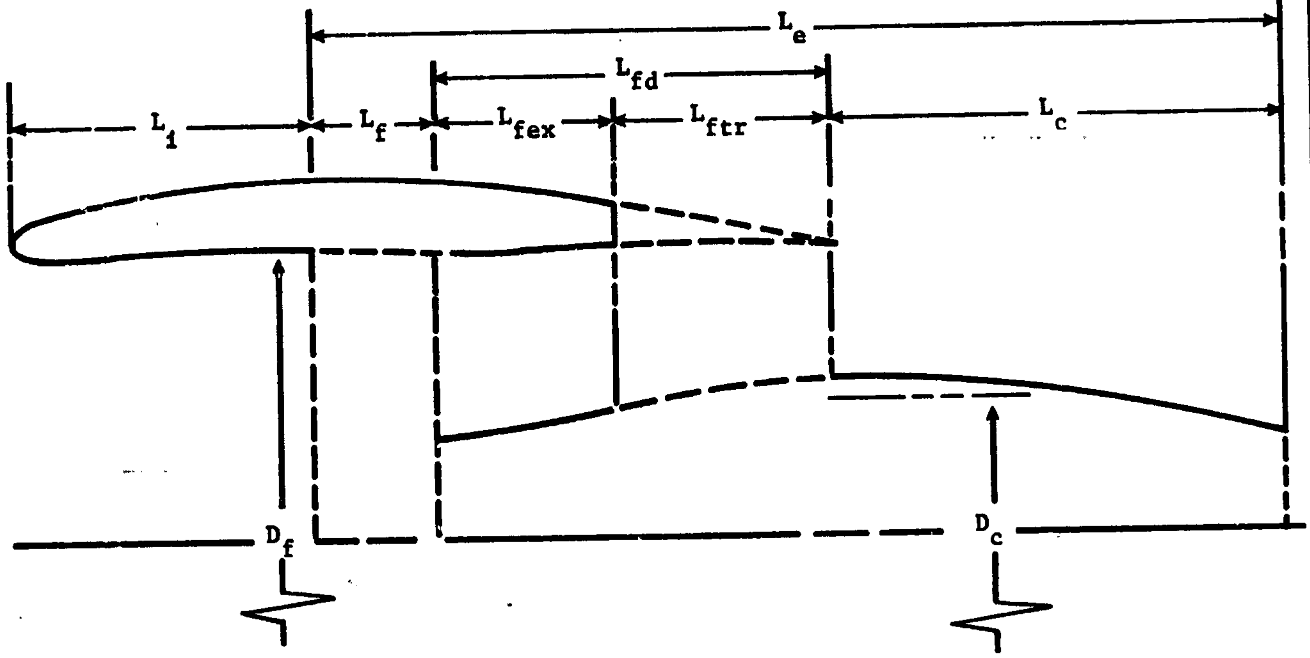


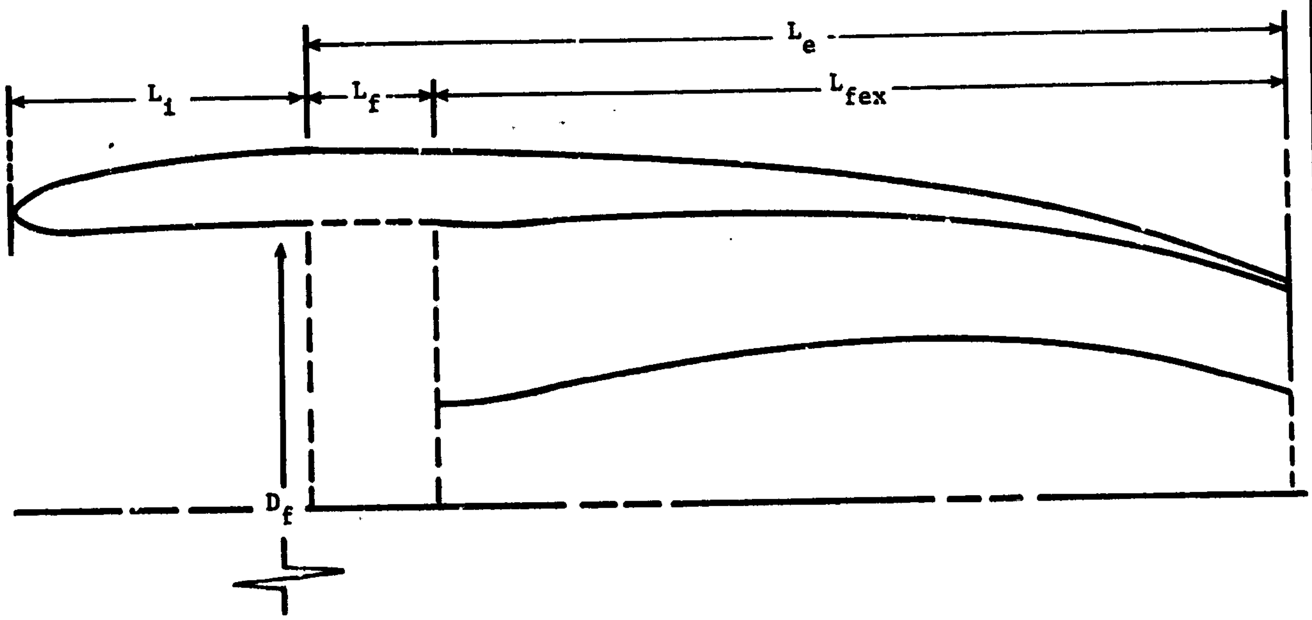
Figure 5.15

NACELLE DIAGRAM

SHORT DUCT NACELLE



LONG DUCT NACELLE



(L_f), 3) the fan exhaust ducting (L_{fex}) which includes the inner bifurcated ducts as well as the outer cowl, and 4) the core cowl (L_c) which is an important part of the fan exhaust ducting especially for long duct designs. The area weighted term for each of the first three segments is determined by multiplying the fan diameter (D_f) by the length of each segment and by pi (π). Thus, the inlet area equals $\pi L_i D_f$ in square inches or $\pi L_i D_f/144$ in square feet. If a dimensional sketch of the cowl structure is not available so that the lengths of the four segments are unknown, the area can be estimated by using values for an existing design as given in Tables 5.6, 5.7 and 5.8 and multiplying this ratio by the square of the fan diameter, i.e. $(L_i/D_f)\pi \times (D_f)^2$. The area of the fourth segment, the core cowl area, is determined by multiplying the average core cowl diameter ($\bar{D}_c$) by L_c and by π .

Weight data were available for each of the four cowl segments, and these weights were divided by the weighted areas of their respective segments. The weights for these cowl segments were then plotted as a function of fan diameter. It was found that tne unit weights of the inlet and fan exhaust ducting increased significantly with fan diameter. However, the fan ccwl and core cowl unit weights were essentially the same and their values were nearly equal. The cowl segment unit weights (in pounds per square foot) may be expressed as follows:

Inlet cowl: $$\frac{W_i}{\pi L_i D_f/144} = 2.5 + 0.0238\, D_f$$

Fan cowl: $$\frac{W_f}{\pi L_f D_f/144} = 1.9$$

Fan exhaust cowl: $$\frac{W_{fex}}{\pi L_{fex} D_f/144} = (2.5 + 0.0363\, D_f)$$

Core cowl: $$\frac{W_c}{\pi L_c D_c/144} = 1.9$$

Therefore, it was possible to develop a cowl weight index by summing the weights of the cowl segments and dividing by $1.9\pi/144 = 0.0415$.

The equation for this index is:

$$I_c = (1.316 + 0.0125\, D_f)\, L_i D_f + L_f D_f + (1.316 + 0.0191\, D_f)\, L_{fex}\, D_f + L_c \overline{D}_c$$

The cowl weight per engine is plotted as a function of this weighted area index (I_c) in Figure 5.16 and shows excellent correlation for conventional subsonic aircraft. Tail mounted nacelle weights are not included and are discussed later.

The equation for the total nacelle cowl weight is:

$$W_{5A} = 0.0415\, N_e I_c$$

where: N_e is the number of engines, and I_c is defined above.

As shown in Figure 5.16, the C-141A aircraft is above the line as it is heavier due to blow-in doors in the inlet. To make the 747 nacelle comparable to the others, each 747 nacelle is reduced by 337 pounds (238 pounds of inlet sound treatment and 99 pounds of flutter ballast). For the JT8D engine on the DC-9, 727 and 737, the fan exhaust ducting is part of the dry engine weight and, therefore, the outer cowl from the engine front face to the engine rear face is included with the fan cowl area and weight since this is more representative of the unit weight for the outer cowl only.

The effect of sound treatment on the cowl weight and cowl weight index is shown in Figure 5.17 based on the data in Table 5.8. For example, the by-pass ratio 6.0 engine cowl shows an increase of about 28 percent in weight and 32 percent in the cowl index as a result of one inch sound treatment and lengthening of the inlet. Thus, for this example, there is a slight decrease in the unit weight of the cowl (W_{5A}/I_e). The weight of

Figure 5.16

NACELLE COWL WER

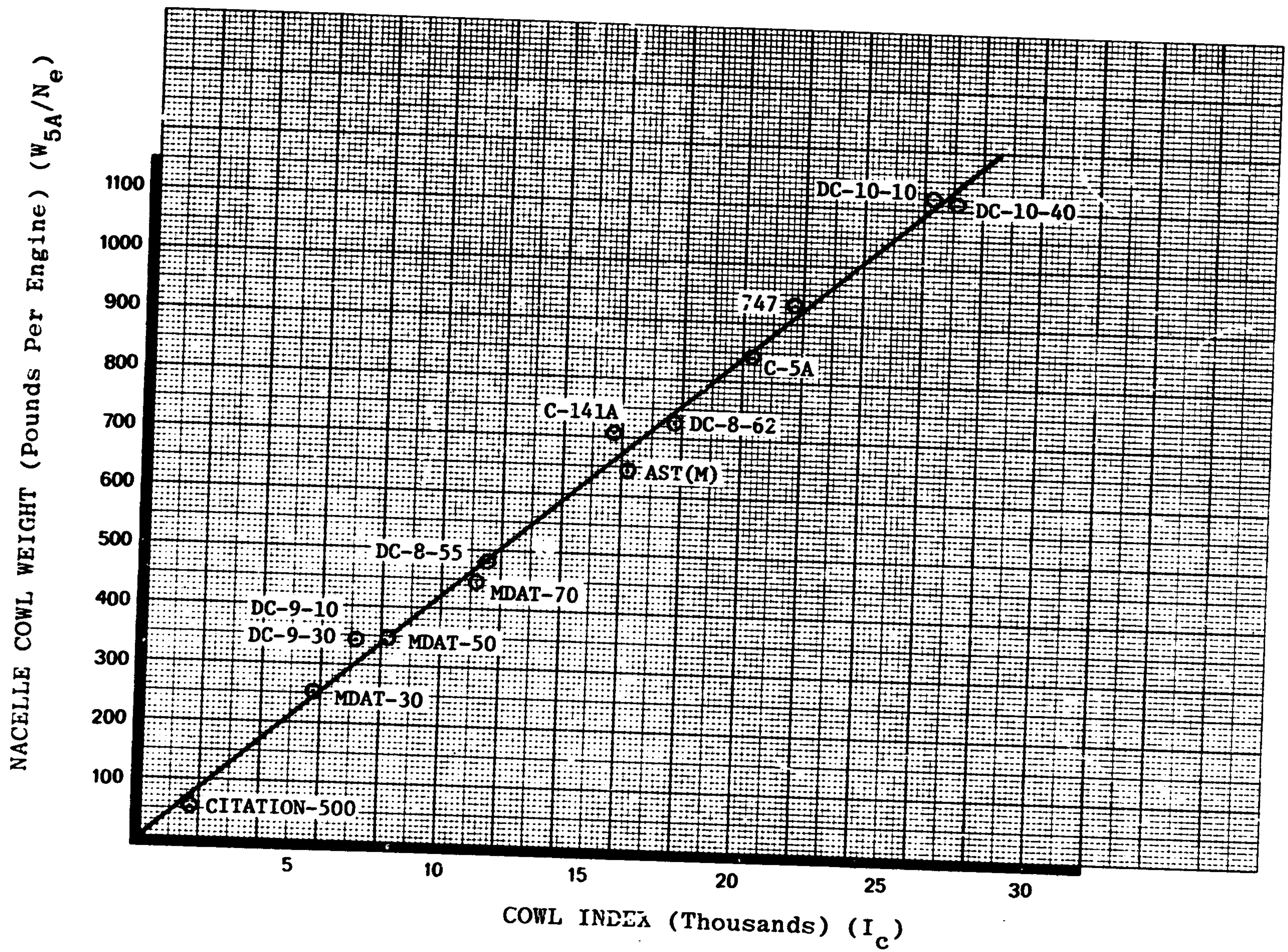
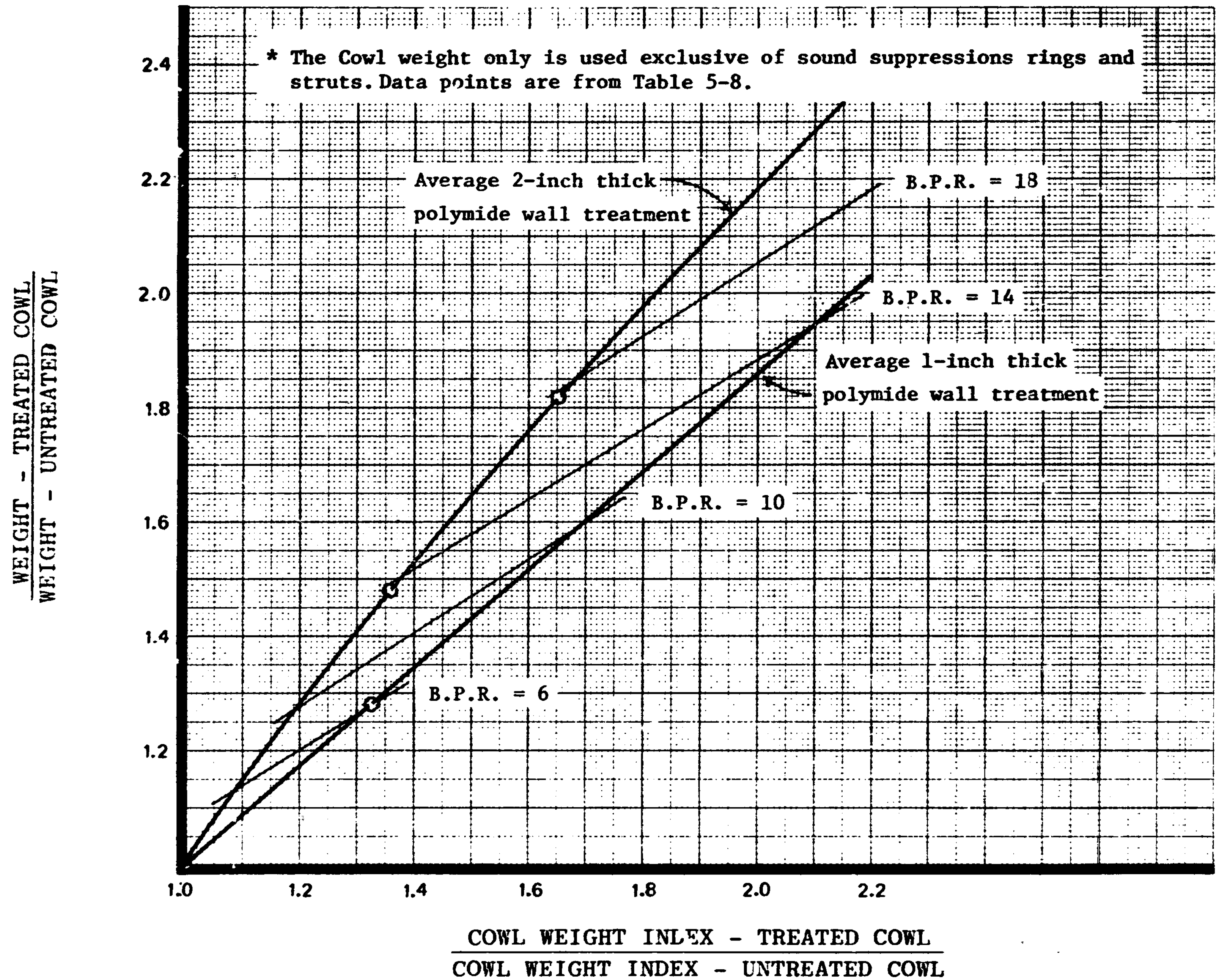


Figure 5.17

WEIGHT EFFECT OF COWL SOUND TREATMENT*



sound suppression rings and struts is not included in the cowl weight plotted in the figure.

Pylon:

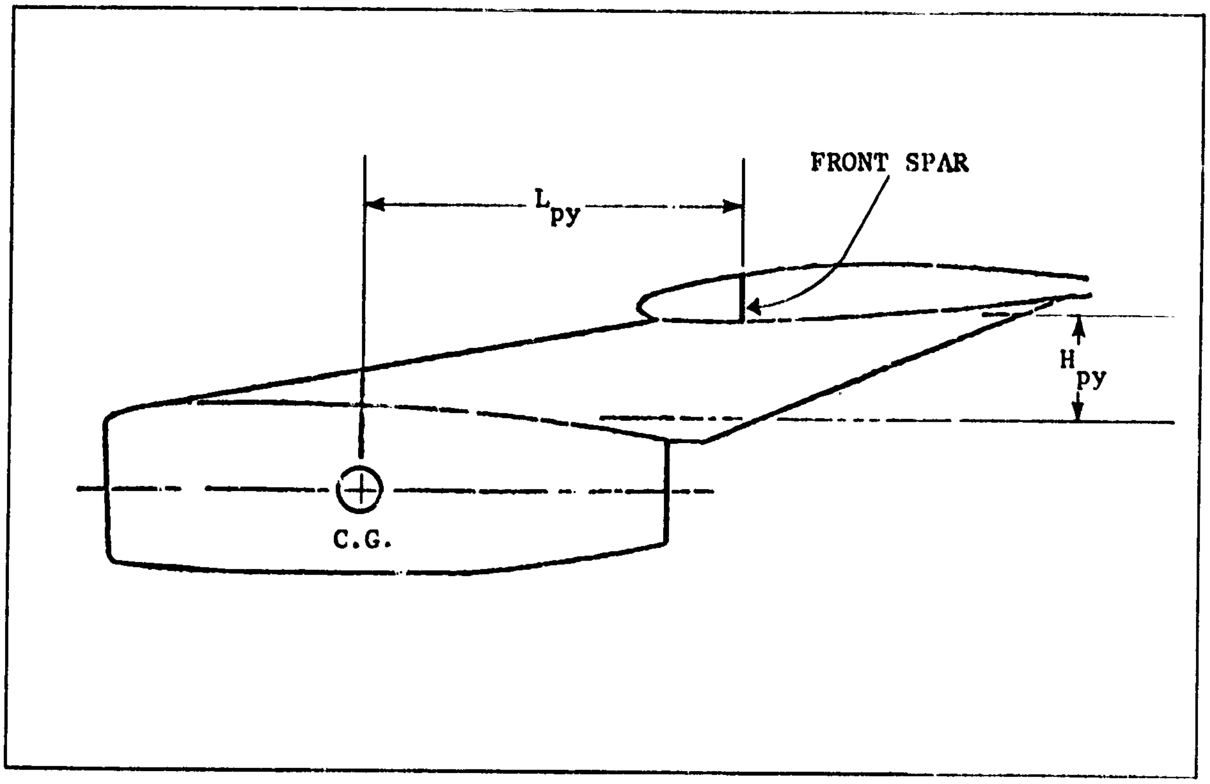
A diagram of a typical wing mounted pylon showing the important characteristic dimensions is given in Figure 5.18. Tail mounted nacelles are discussed later. Pylons have four characteristics which have a significant effect on their weight. They are:

1) The demountable weight of the power plant pod (W_{dem}). This is the weight of the cowl (W_{5A}) and the propulsion system including the dry engine weight (W_6 + engine weight) but less the fuel system weight (W_{6E}). Weights for engine mounted components such as hydraulic pumps (hydraulic system) and generators (electrical system) were not considered since they represent only a small portion of the demountable weight and since their elimination simplifies the determination of pylon weight.

2) The horizontal distance from the wing front spar to the demountable center of gravity (L_{py}) which, when combined with W_{dem}, is an indicator of the moment applied to the pylon. The center of gravity position of various engine installations was examined and found to average about half of the distance between the inlet lip and the tip of the tailpipe or primary thrust reverser. Also, it was found that the moment (W_{dem}) (L_{py}) should be increased about 20 percent for STOL type aircraft with sink speeds of about 18 feet-per-second.

3) The height of the pylon box (H_{py}). For pylons, as shown in the diagram, this value is the distance from the bottom of the wing to the top of the nacelle. For high by-pass ratio, short duct engines, this value is usually the distance between the top of the core cowl and the bottom of the wing. For pylons which extend above and around the leading edge of the wing, half the wing depth at the front spar is added to this value.

Figure 5.18
PYLON DIAGRAM



4) The side profile area of the pylon (S_{py}). This area can be estimated from a nacelle installation sketch like that shown in Figure 5.18.

It was expected that the pylon unit weight (pounds per square foot of side profile area) might be proportional to W_{dem} and L_{py} and inversely proportional to H_{py} and S_{py}. This assumption may be expressed as follows:

$$\frac{W_{5B}}{S_{py}} = f\left(\frac{W_{dem}\ L_{py}}{H_{py}\ S_{py}}\right)$$

If a pylon index is defined as:

$$I_{py} = \frac{W_{dem}\ L_{py}}{H_{py}\ S_{py}}$$

then: $$\frac{W_{5B}}{S_{py}} = a + b\ I_{py}$$

where: W_{5B} = pylon weight, and

a and b are coefficients.

The pylon index helps to predict the effect of cantilevering the engine off the wing. The correlation of unit pylon weight with the pylon index results in the following equation:

$$W_{5B} = S_{py}\ N_e\ (8.0 + 0.0144\ I_{py})$$

where I_{py} is defined above. The pylon weight correlation is very good as indicated by the plot in Figure 5.19 of actual weight versus estimated weight using the above equation. The DC-10 pylons are shown only for reference since they are heavier due to the addition of stiffness material to reduce nacelle flutter. The fuselage mounted DC-9 pylon also correlated well by defining L_{py} as the distance from the side of the fuselage to the cowl and H_{py} as the pylon thickness.

<u>Tail Mounted Nacelle</u>:

The weights of the tail mounted nacelles are shown in Figure 5.20. The "S" duct configuration shows a significant weight penalty relative to

Figure 5.19

PYLON WER

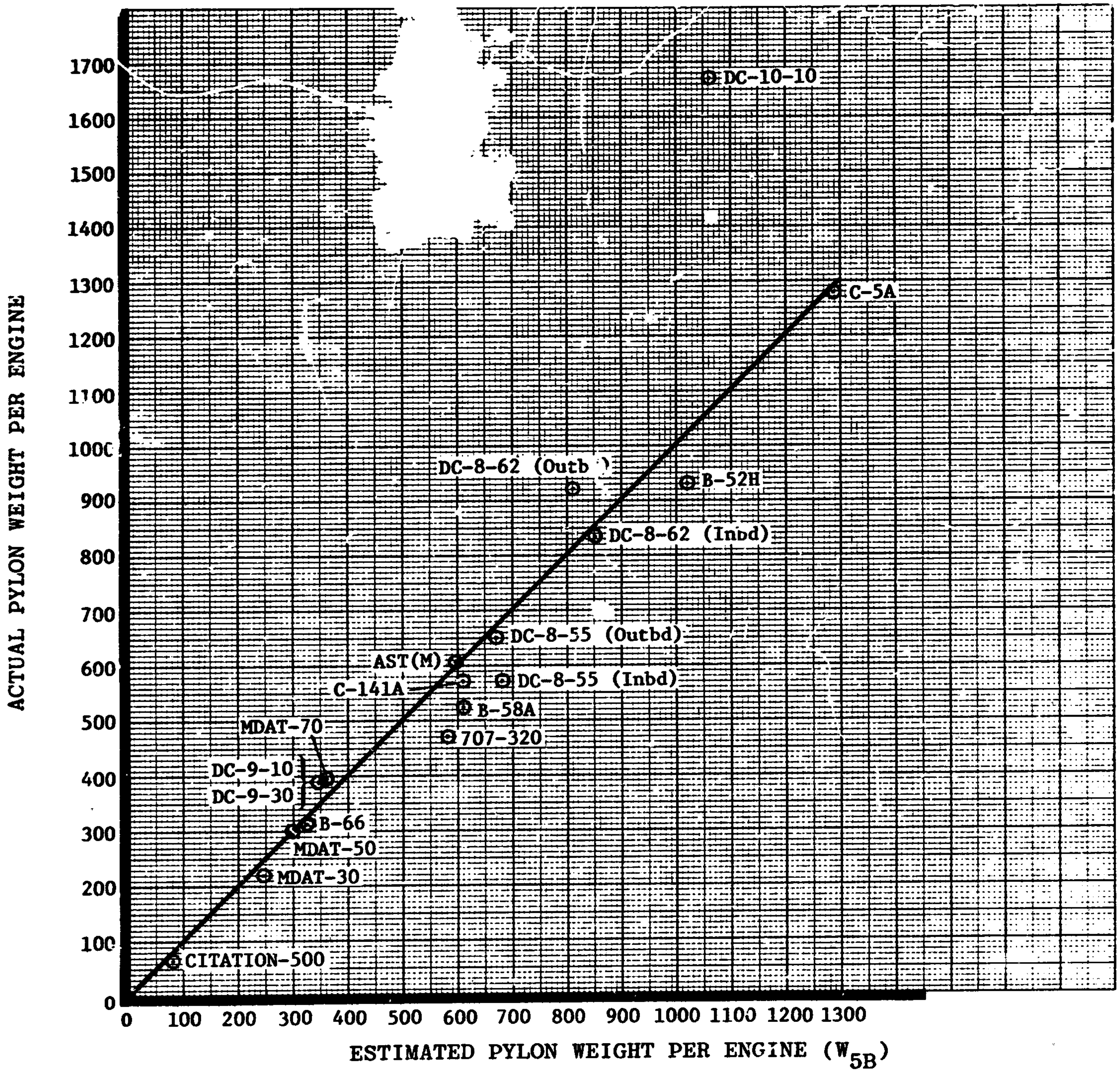
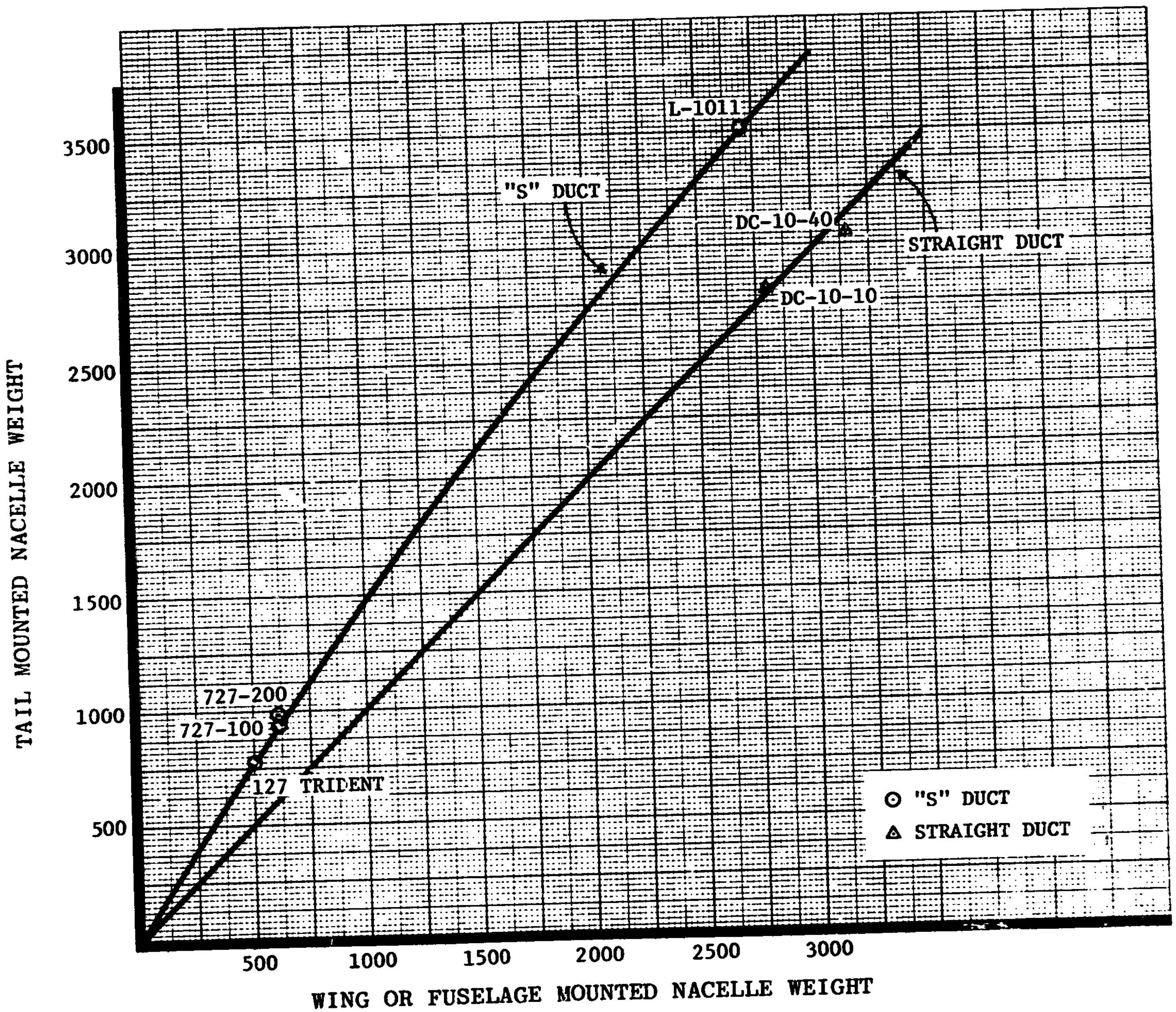


Figure 5.20

WEIGHT TREND-WING MOUNTED Vs. TAIL MOUNTED NACELLE (INCLUDING PYLON)
(Pounds per engine)



a normal wing or fuselage mounted nacelle. Based on the data for the DC-10 design, the straight through duct tail mounted nacelle weighs about the same as the wing or fuselage mounted nacelle. Carry through structure between the tail and the fuselage for the straight through design including both frames around the engine and the tail stub are included with the tail. Body shell structure and support frames are included with the body.

Since the straight duct tail mounted nacelle weighs about the same as a wing or fuselage mounted nacelle cowl and pylon, the WERs for cowl and pylon discussed earlier are used. For a tail mounted nacelle with an "S" duct, the following weight must be added to the weight of the cowl and pylon determined from the WERs discussed earlier:

$$W_{5C} = 3.04\ [(W_{5A} + W_{5B})/N_e]^{0.893} - (W_{5A} + W_{5B}/N_e)$$

D. PROPULSION SYSTEM (LESS ENGINE)

Weight and Design Characteristics

Weight data for the propulsion system are presented in Tables 5.9 and 5.10 for commercial and military transport aircraft, respectively. The propulsion system is divided into three subsystems: thrust reverser, fuel system and engine systems. These are the same subsystems for which CERs were derived. Related propulsion system design characteristics are also presented in Tables 5.9 and 5.10; notations are given to indicate the types of thrust reverser configurations. All thrusts are sea level, static and uninstalled.

The data in Tables 5.9 and 5.10 include aircraft with wing, fuselage and tail mounted turbofan and turbojet engines. In addition the proposed CFM-56 engine is shown in one of its study configurations to indicate the separate engine exhaust flow system weight without thrust reverser. The C-133B aircraft, which has turboprop engines, was included only to provide additional fuel system information.

Weight Estimating Relationships

Separate WERs were developed for the thrust reverser, fuel system and engine systems.

Thrust Reverser:

The thrust reverser includes the exhaust system. Diagrams of thrust reversers and exhaust nozzles which cover most of the current power plant configurations are provided in Figure 5.21. Only one high by-pass fan thrust reverser system is illustrated (a), as this is the only type of fan reverser system used on aircraft in the data base. Other diagrams show engine exhaust configurations for separate and mixed flow designs. Figures (b) and (f) represent short duct designs with and without thrust reversers. The other three diagrams represent long duct designs with reversers (c and d) and without reversers (e). The solid lines in the diagrams represent the portion of the nacelle system that is covered by the thrust reversers and exhaust sections.

Table 5.9

PROPULSION SYSTEM WEIGHT AND DESIGN DATA - COMMERCIAL AIRCRAFT

	Symbol	Citation 500 JT15D-1	MDAT-30 —	MDAT 50 —	MDAT-70 —	DC-9-10 JT8D-5	BAC 111 MK.512-14DW	DC-9-30 JT8D-9	737-200 JT8D-7	727-100 JT8D-7
Weight Data										
Propulsion	W_6	340	1,140	1,338	1,702	1,478	1,788	2,190	1,721	3,052
Thrust Reverser and Exhaust System	W_{6A}	34	697	943	1,225	780	621	784	971	1,698
Fan	W_{6A1}	—	394	533	698	—	—	—	—	—
Engine	W_{6A2}	34	303	410	527	780	621	784	971	1,698
Fuel System	W_{6B}	194	347	265	305	514	575	1,216	544	949
Wing		194	227	265	305	514	575	587	544	949
Supplemental		—	120	—	—	—	—	629	—	—
Engine Systems	W_{6C}	112	96	130	172	184	592	190	206	405
%MEW		5.3	5.6	5.0	5.0	3.1	3.5	3.9	3.0	3.6
Design Data										
Fan Thrust Reverser/Engine										
Type		—	a	a	a	—	—	—	—	—
Thrust (lbs.)	T_{ftr}	—	5,530	7,515	9,790	—	—	—	—	—
Length (in.)	L_{ftr}	—	14.4	16.8	19.1	—	—	—	—	—
Primary Thrust Reverser and Exhause/Eng.										
Type		g	g	g	g	d	—	d	d	d
Thrust (lbs.)	T_{ptr}	2,200	6,450	8,770	11,420	12,250	12,550	14,500	14,000	14,000
Diameter (in.)	D_t	19.0	26.1	30.5	34.8	38.0	—	38.0	—	—
Length (in.)	L_{pex}	9.5	34.7	40.5	46.2	53.0	—	53.0	—	—
Ratio	D_t/D_f	0.905	0.586	0.586	0.586	0.905	—	0.905	—	—
Ratio	L_{pex}/L_{ftr}	—	2.4	2.4	—	—	—	—	—	—
Fuel System										
Number of tanks	N_{ft}	2	3	3	3	3	3	3	3	3
Fuel Volume (gals.)	G_{ft}	583	1,068	1,449	2,182	3,685	3,723	4,259	3,439	7,174
Wing Span		43.7	55.5	64.6	73.8	89.6	93.4	93.4	93.0	108.0

a. Fan exhaust cascade type thrust reverser with translation sleeve.
b. Cascade or target type thrust reverser with translating sleeve.
c. Simple target type thrust reverser with separate flow exhaust nozzle.
d. Simple target type thrust reverser with mixed flow exhaust nozzle.
e. Separate flow primary exhaust system without thrust reverser.
f. Short duct type primary exhaust system without thrust reverser.
g. Long duct mixed flow exhaust nozzle without thrust reverser.

Table 5.9 (Continued)

PROPULSION SYSTEM WEIGHT AND DESIGN DATA - COMMERCIAL AIRCRAFT

	Symbol	727-200 JT8D-9	707-320 JT4A-5	DC-8-55 JT3D-3B	DC-8-62 JT3D-3B	DC-10-10 CF6-6D	L-1011 RB211-22B	DC-10-40 JT9D-15	747 JT9D-7
Weight Data									
Propulsion	W_6	3,022	5,306	9,410	7,840	7,673	8,279	13,503	9,605
Thrust Reverser and Exhaust System	W_{6A}	1,557	2,242	5,100	4,468	5,382	5,971	7,851	6,331
Fan	W_{6A1}	—	—	2,118	—	4,014	4,510	5,274	3,489
Engine	W_{6A2}	1,557	2,242	2,912	4,468	1,368	1,461	2,577	2,842
Fuel System	W_{6B}	1,080	1,956	3,081	2,780	1,850	1,588	4,230	2,335
Wing		1,080	1,956	3,081	2,780	1,850	1,588	2,187	2,335
Supplemental		—	—	—	—	—	—	2,043	—
Engine Systems	W_{6C}	385	1,108	1,229	592	441	720	1,422	939
%MEW		3.2	4.2	7.0	5.8	3.4	3.7	5.4	3.0
Design Data									
Fan Thrust Reverser/Engine									
Type		—	—	a	—	a	a	a	a
Thrust (lbs.)	T_{ftr}	—	—	10,200	—	34,200	35,000	37,400	37,800
Length (in.)	L_{ftr}	—	—	35.0	—	46.0	—	62.0	25.0
Primary Thrust Reverser and Exhause/Eng.									
Type		d	b	b	b	b	b	b	b
Thrust (lbs.)	T_{ptr}	14,500	18,000	7,800	18,000	5,800	7,000	7,600	7,700
Diameter (in.)	D_t	—	—	41.0	41.0	50.0	—	59.0	59.0
Length (in.)	L_{pex}	—	—	54.0	58.0	25.0	—	57.0	43.
Ratio	D_t/D_f	—	—	0.774	0.774	0.538	—	0.615	0.615
Ratio	L_{pex}/L_{ftr}	—	—	1.54	—	0.543	—	0.919	0.123
Fuel System									
Number of tanks	N_{ft}	3	6	11	9	6	6	7	7
Fuel Volume (gals.)	G_{ft}	8,186	21,262	23,392	24,259	21,672	22,985	36,561	47,210
Wing Span		108.2	142.4	142.4	148.3	155.4	155.3	165.4	195.7

a. Fan exhaust cascade type thrust reverser with translation sleeve.
b. Cascade or target type thrust reverser with translating sleeve.
c. Simple target type thrust reverser with separate flow exhaust nozzle.
d. Simple target type thrust reverser with mixed flow exhaust nozzle.
e. Separate flow primary exhaust system without thrust reverser.
f. Short duct type primary exhaust system without thrust reverser.
g. Long duct mixed flow exhaust nozzle without thrust reverser.

Table 5.10

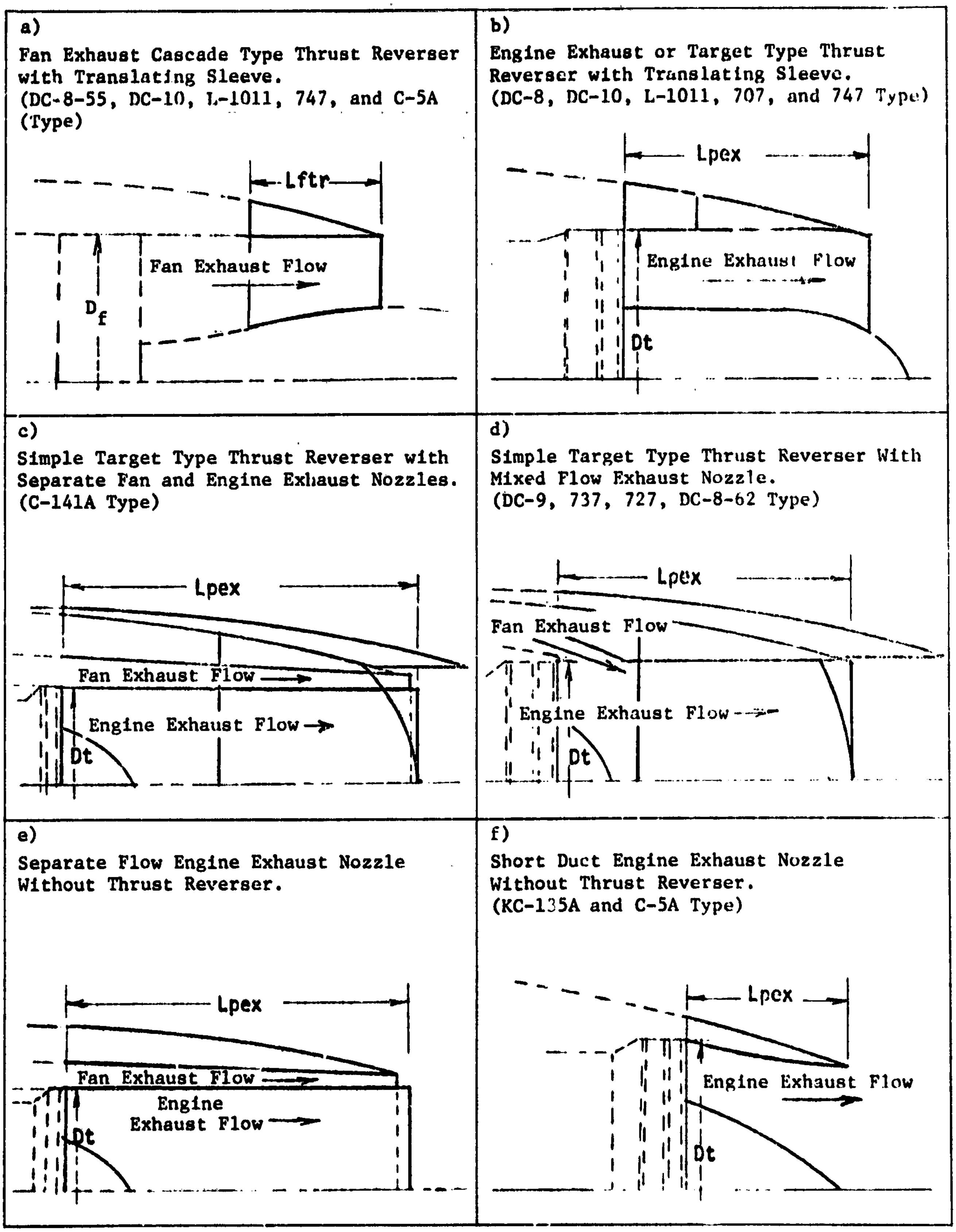
PROPULSION SYSTEM WEIGHT AND DESIGN DATA - MILITARY AIRCRAFT

	Symbol	KC-135A J57-P-43	C-133B --	C-141A TF33-P-7	C-5A TF 39	-- CFM 56
Weight Data						
Propulsion	W_6	6,489	--	5,780	6,813	561 lb/eng
Thrust Reverser and Exhaust System	W_{6A}	106	--	3,294	3,816	561 lb/eng
Fan	W_{6A1}	--	--	--	3,264	--
Engine	W_{6A2}	106	--	3,294	552	561
Fuel System	W_{6B}	5,436	2,001	1,566	2,429	--
Wing		1,430	1,425	1,566	2,429	--
Supplemental		4,006	576	--	--	--
Engine Systems	W_{6C}	947	--	920	568	--
%MEW		7.0	--	4.5	2.1	--
Design Data						
Fan Thrust Reverser/Engine						
Type		--	--	--	a	--
Thrust (lbs.)	T_{ftr}	--	--	--	36,500	--
Length (in.)	L_{ftr}	--	--	--	18.0	--
Primary Thrust Reverser and Exhause/Eng.						
Type		f	--	c	f	e
Thrust (lbs.)	T_{ptr}	13,750	--	21,000	4,500	22,000
Diameter (in.)	D_t	--	--	41.0	50.0	41.0
Length (in.)	L_{pex}	--	-	60.0	20.0	55.0
Ratio	D_t/D_f	--	--	0.774	0.521	0.577
Ratio	L_{pex}/L_{ftr}	--	--	--	1.11	2.50
Fuel System						
Number of tanks	N_{ft}	7	8	10	12	--
Fuel Volume (gals.)	G_{ft}	26,955	18,236	23,694	49,000	--
Wing Span		130.8	179.7	160.7	222.7	--

a. Fan exhaust cascade type thrust reverser with translation sleeve.
b. Cascade or target type thrust reverser with translating sleeve.
c. Simple target type thrust reverser with separate flow exhaust nozzle.
d. Simple target type thrust reverser with mixed flow exhaust nozzle.
e. Separate flow primary exhaust system without thrust reverser.
f. Short duct type primary exhaust system without thrust reverser.
g. Long duct mixed flow exhaust nozzle without thrust reverser.

Figure 5.21

THRUST REVERSER AND EXHAUST NOZZLE CONFIGURATIONS



Thrust reverser weights vary considerably depending on configuration. It was, therefore, necessary to develop separate WERs for each of the six thrust reverser types shown in Figure 5.21. There are two characteristics which have a significant effect on the weight of the thrust reverser. The first is the enclosing area of the thrust reverser (and exhaust system). For fan reversers, the area is approximately the fan diameter times the length of the fan thrust reverser translating nozzle ($\pi D_f L_{ftr}/144$). For the engine exhaust section, the turbine exhaust flange diameter times the length of the engine exhaust nozzle is used ($\pi D_t L_{pex}/144$). If D_t and L_{pex} are not known, they can be estimated by using values for the ratios D_t/D_f and L_{pex}/L_{ftr} and dimensions D_t and L_{ftr} from an existing design, as given in Tables 5.9 and 5.10, that is similar to the desired design.

The second important characteristic is engine thrust. Where the engine has both a fan thrust reverser and engine exhaust thrust reverser, the total thrust (T) is split based on the engine by-pass ratio (BPR) as follows:

$$T_{ftr} = \frac{(BPR)(T)}{1 + BPR}$$

$$T_{ptr} = \frac{T}{1 + BPR}$$

Total thrust and by-pass ratio are given in Tables 5.6 and 5.7.

The weights of the thrust reversers were correlated with thrust and enclosing area of the thrust reverser in order to develop WERs for each type. The unit weight equation has the following form:

$$\frac{W_6}{DL} = f\ (a+b\ \frac{T}{DL})$$

For <u>fan thrust reversers</u>:

$$\frac{W_{6A1}}{\pi D_f\ L_{ftr}/144} = 10.0 + 0.0120\ \frac{T_{ftr}}{\pi D_f\ L_{ftr}/144}$$

where: W_{6A1} = fan thrust reverser weight

Note that the zero intercept is about 10 lb/ft^2. The WER is therefore:

$$W_{6A1} = (0.218\ D_f\ L_{ftr} + 0.0120\ T_{ftr})\ N_e$$

The correlation is very good as indicated by the plot of actual weights versus estimated weights in Figure 5.22. Due to the short fan thrust reverser design for the 747, its fan cascades are partially stowed over the aft section of the fan case. This accounts for the relatively low 747 weight.

For <u>engine exhaust reversers and nozzles</u>:

$$\frac{W_{6A2}}{\pi\ D_t\ L_{pex}/144} = a + b\ \frac{T_{ptr}}{\pi\ D_t\ L_{pex}/144}$$

where: W_{6A2} = engine exhaust reverser and nozzle weight and
a,b are coefficients.

The WERs for the different configurations are:

Cascade or Target Type Reverser with Translating Sleeve:

$$W_{6A2} = (0.179\ D_t\ L_{pex} + 0.0389\ T_{ptr})\ N_e$$

Simple Target Type Reverser with Separate Flow Exhaust Nozzle:

$$W_{6A2} = (0.131\ D_t\ L_{pex} + 0.0239\ T_{ptr})\ N_e$$

Simple Target Type Reverser with Mixed Flow Exhaust Nozzle:

$$W_{6A2} = 0.105\ D_t\ L_{pex} + 0.0122\ T_{ptr})\ N_e$$

Separate Flow Engine Exhaust System Without Thrust Reverser:

$$W_{6A2} = (0.113\ D_t\ L_{pex} + 0.0144\ T_{ptr})\ N_e$$

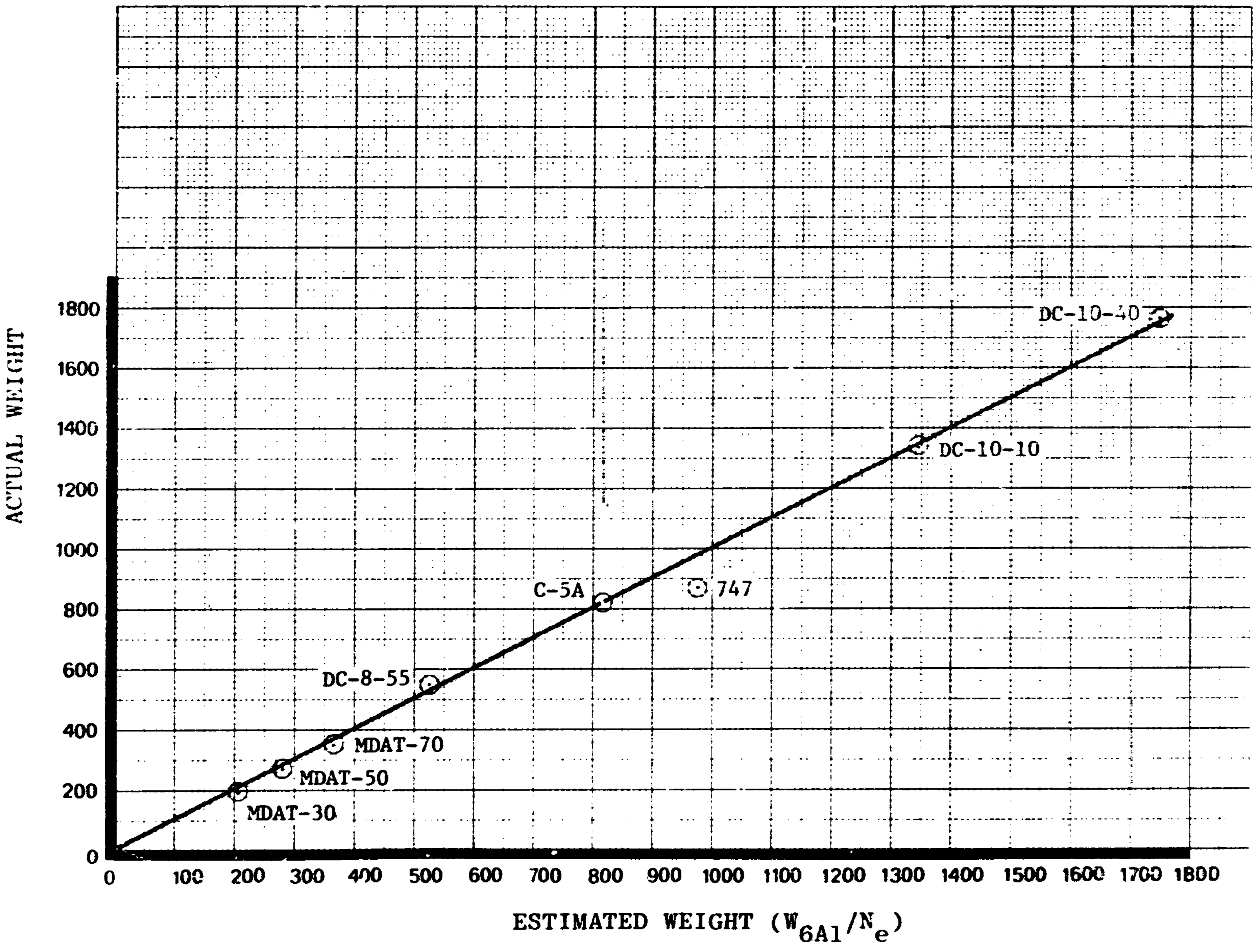
Short Duct Engine Exhaust System Without Thrust Reverser:

$$W_{6A2} = (0.096\ D_t\ L_{pex} + 0.0094\ T_{ptr})\ N_e$$

Figure 5.22

BYPASS FAN THRUST REVERSER ACTUAL Vs. ESTIMATED WEIGHTS

(Pounds per Engine)



Correlations are very good as shown by the plot of actual versus estimated weights in Figure 5.23.

Fuel System:

Fuel system weight was correlated with several different characteristics including fuel volume, number of tanks and wing span. Wing span (L_w) times the number of fuel tanks (N_{ft}) provided the best results. The wing span indicates the run lengths for fill, distribution and vent plumbing. The number of tanks indicates the number of pumps and valves. The fuel system weights are plotted in Figure 5.24. Separate WERs were developed for commercial and military aircraft. The underlying reasons for the large differences between commercial and military aircraft are not known. Some differences were found in the fuel distribution system, but there were insufficient data to determine the reason for these differences as no evidence was found which would indicate appreciable design philosophy differences between military and commercial transports.

The WERs are:

$$W_{6B} = 2.71 \, (L_w \, N_{ft})^{0.956} \qquad \text{Commercial}$$

$$W_{6E} = 0.920 \, L_w \, N_{ft} \qquad \text{Military}$$

Weights for supplemental fuel tanks are excluded for the purposes of comparability among the aircraft. However, aircraft statistical data and design study results indicate that unit weights for supplemental tanks range from about 0.5 lb./gal. for integral or bladder type belly tanks to 1.0 lb./gal. for self-contained metal type tanks.

Engine Systems:

The engine system weights shown in Tables 5.9 and 5.10 vary considerably due in part to differences in engine operating requirements (e.g., water injection and auto throttle). Also, in some cases the engine systems may be included as standard equipment on the dry engine. However when the engine

Figure 5.23

ENGINE EXHAUST THRUST REVERSER AND NOZZLE ACTUAL WEIGHT Vs. ESTIMATED WEIGHTS*

(Pounds per engine)

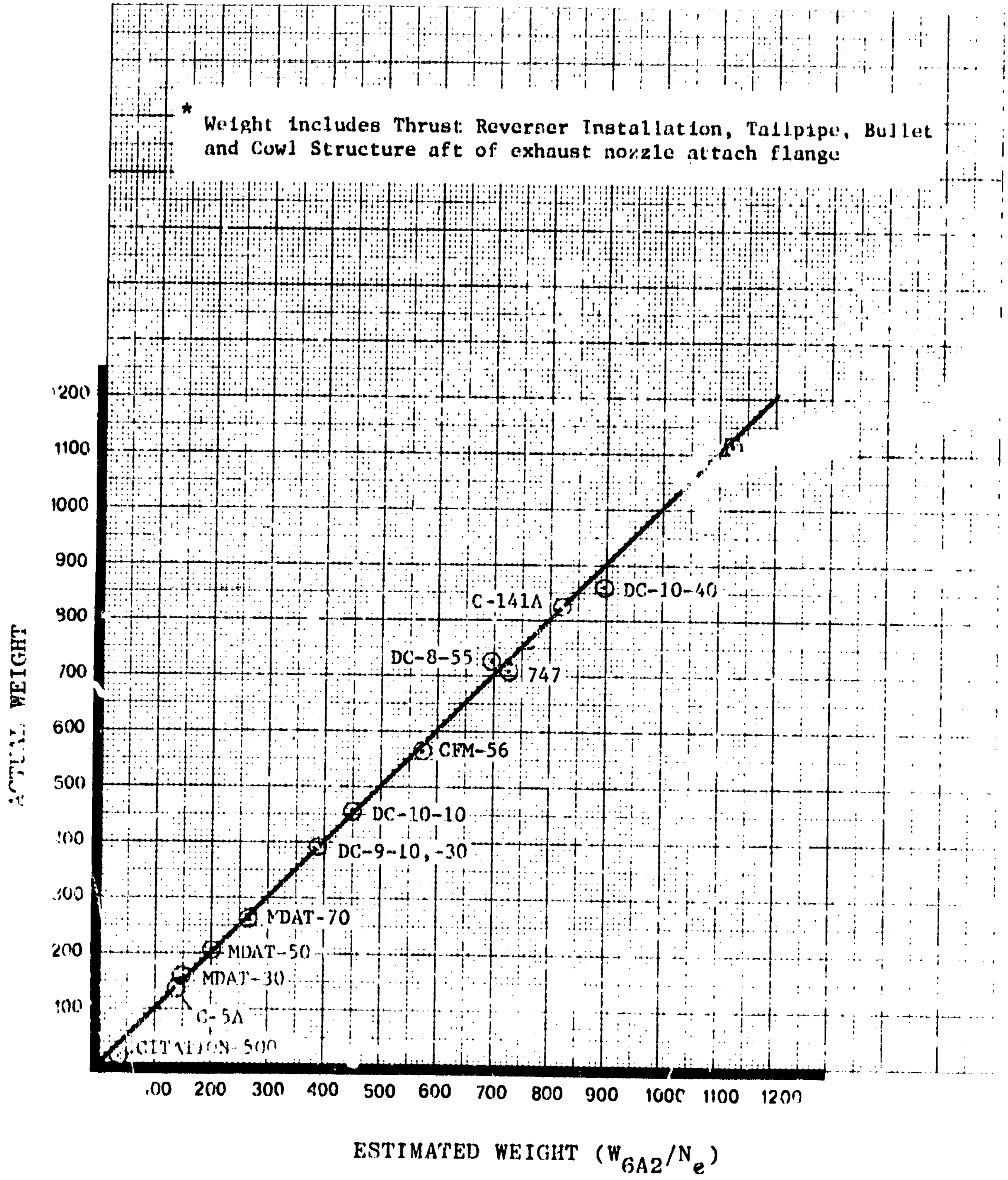
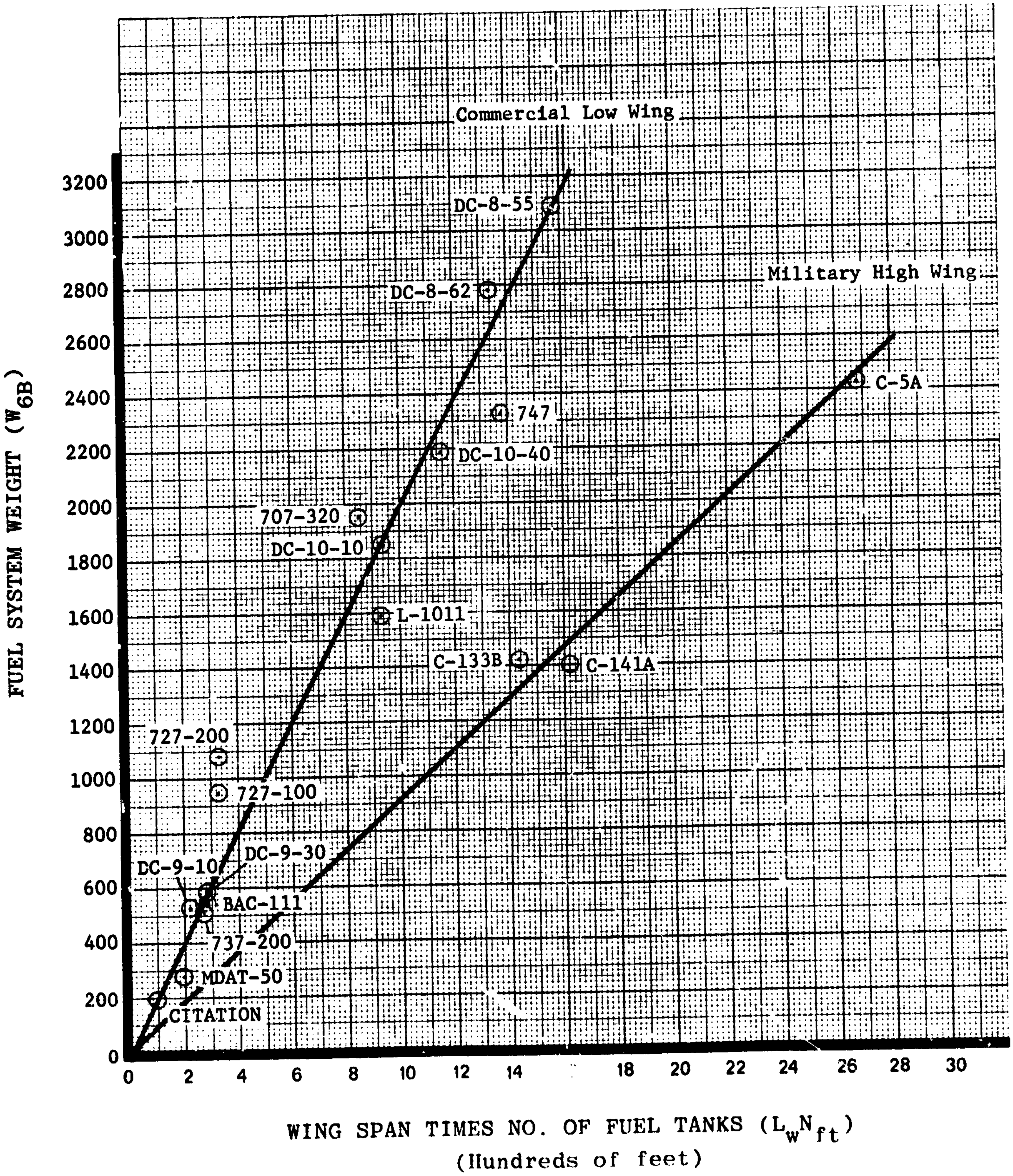


Figure 5.24

FUEL SYSTEM WERs



system weights were adjusted to delete water injection and auto throttle, the systems for the MDAT 70, DC-9-10, BAC-111, DC-9-30, 737-200, 727-100, 727-200, DC-8-62, DC-10-10, DC-10-40, and C-5A seem comparable. For these models, the adjusted weight per engine ranges from 84 to 151 pounds with no correlation to engine size. Thus, an average of 117 pounds is appropriate. If auto throttle is included, the average weight is 133 pounds per engine. Either of the two values should provide satisfactory advance design weights.

$$W_{6C} = 117\ N_e \qquad \text{Without auto throttle}$$

$$W_{6C} = 133\ N_e \qquad \text{With auto throttle}$$

E. FLIGHT CONTROLS AND HYDRAULIC SYSTEMS

The flight controls and hydraulic power systems weights are combined for weight correlation purposes because of variations in functional weight allocations and system interpretation among aircraft manufacturers, and also because a large portion of the aircraft hydraulic power system is designed by the flight control hydraulic actuation requirements of flow rates and system redundancy. These requirements create a natural interdependence between the two systems and it is, therefore, difficult to develop separate WERs that are meaningful. However, approximate WERs are developed for each system based on its percentage of the combined flight control and hydraulic systems weight.

Weight and Design Characteristics

Weight and design characteristics for the flight controls and hydraulics systems are presented in Tables 5.11 and 5.12 for commercial and military aircraft, respectively. The flight control system weight excludes the autopilot which is included with the avionics system as discussed earlier.

Weight Estimating Relationships

A major influence on the weight of these systems is whether a single hydraulic or multi-hydraulic system is used. The 707, DC-8 and KC-135 aircraft have single hydraulic systems which means a lighter hydraulic system that uses more mechanical controls. Control surface area and the combined wing and tail area also correlate with combined system weight. Weight is shown as a function of control surface area in Figure 5.25. The equations, which represent the two curves, are:

$$W_7 + W_8 = 87.0 + 2.17\, S_{cs}^{0.973} \qquad \text{Single Hydraulic System}$$

$$W_7 + W_8 = 360 + 2.525\, S_{cs} \qquad \text{Multi-Hydraulic System}$$

Alternative equations were also developed based on combined wing and tail area. The tail area is weighted by a factor of 1.44 based on the relative wing and tail flight control weights. Weight is shown as a

Table 5.11

FLIGHT CONTROLS AND HYDRAULICS SYSTEMS WEIGHT AND DESIGN DATA - COMMERCIAL AIRCRAFT

	Symbol	Citation 500	MDAT-30	MDAT-50	F-28	MDAT-70	DC-9-10	BAC-111	DC-9-30	737-200
Weight Data										
Flight Controls and Hydraulics	W_7+W_8	273	771	899	1,746	1,035	1,520	2,390	1,909	2,830
Flight Controls	W_7	196	600	699	1,404	805	1,102	1,655	1,434	2,325
Hydraulics	W_8	77	171	200	342	230	418	735	475	505
Hydraulics as % of Combined		28.2	22.2	22.2	19.6	22.2	27.5	30.8	24.9	17.8
%MEW		4.2	3.8	3.4	5.2	3.0	3.1	4.6	3.4	5.0
Design Data										
Flight Controls										
Wing Area	S_w	269	342	464	822	605	934	1,014	1,001	1,100
Tail Area	S_t	123	216	257	485	324	437	438	437	536
--	$S_w + 1.44S_t$	446	653	834	1,520	1,072	1,563	1,645	1,630	1,872
Control Surface Area	S_{cs}	98	315	407	--	525	643	620	764	--
Hydraulics										
Number of Independent Systems		1	1	1	2	1	2	2	2	2
Number of Engine Driven Pumps		2	2	2	4	2	2	2	2	2

Table 5.11 (Continued)

FLIGHT CONTROLS AND HYDRAULICS SYSTEMS WEIGHT AND DESIGN DATA - COMMERCIAL AIRCRAFT

	Symbol	727-100	727-200	707-320	DC-8-55	DC-8-62	DC-10-10	L-1011	DC-10-40	747	SCAT-15
Weight Data											
Flight Controls and Hydraulics	W_7+W_8	3,463	3,578	2,637	2,715	2,785	7,483	7,599	7,577	9,666	16,377
Flight Controls	W_7	2,836	2,930	2.139	2,035	2,098	5,120	5,068	5,188	6,886	10,777
Hydraulics	W_8	627	648	498	680	687	2,363	2,531	2,389	2,780	5,600
Hydraulics as % of Combined		18.1	18.1	18.9	25.0	24.7	31.6	33.3	31.5	28.8	34.2
%MEW		4.2	3.7	2.1	2.1	2.1	3.3	3.4	3.1	3.0	5.4
Design Data											
Flight Controls											
Wing Area	S_w	1,650	1,520	2,892	2,883	2,927	3,550	3,456	3,610	4,960	10,744
Tail Area	S_t	761	761	937	827	827	1,617	1,656	1,617	2,030	586
—	$S_w + 1.44S_t$	2,746	2,616	4,241	4,074	4,118	5,878	5,841	5,938	7,883	11,588
Control Surface Area	S_{cs}	1,193	1,193	1,551	1,469	1,469	3,028	2,812	3,032	3,719	2,753
Hydraulics											
Number of Independent Systems		2	2	1	1	1	3	3	3	4	4
Number of Engine Driven Pumps		2	2	2	2	2	6	6	6	8	8

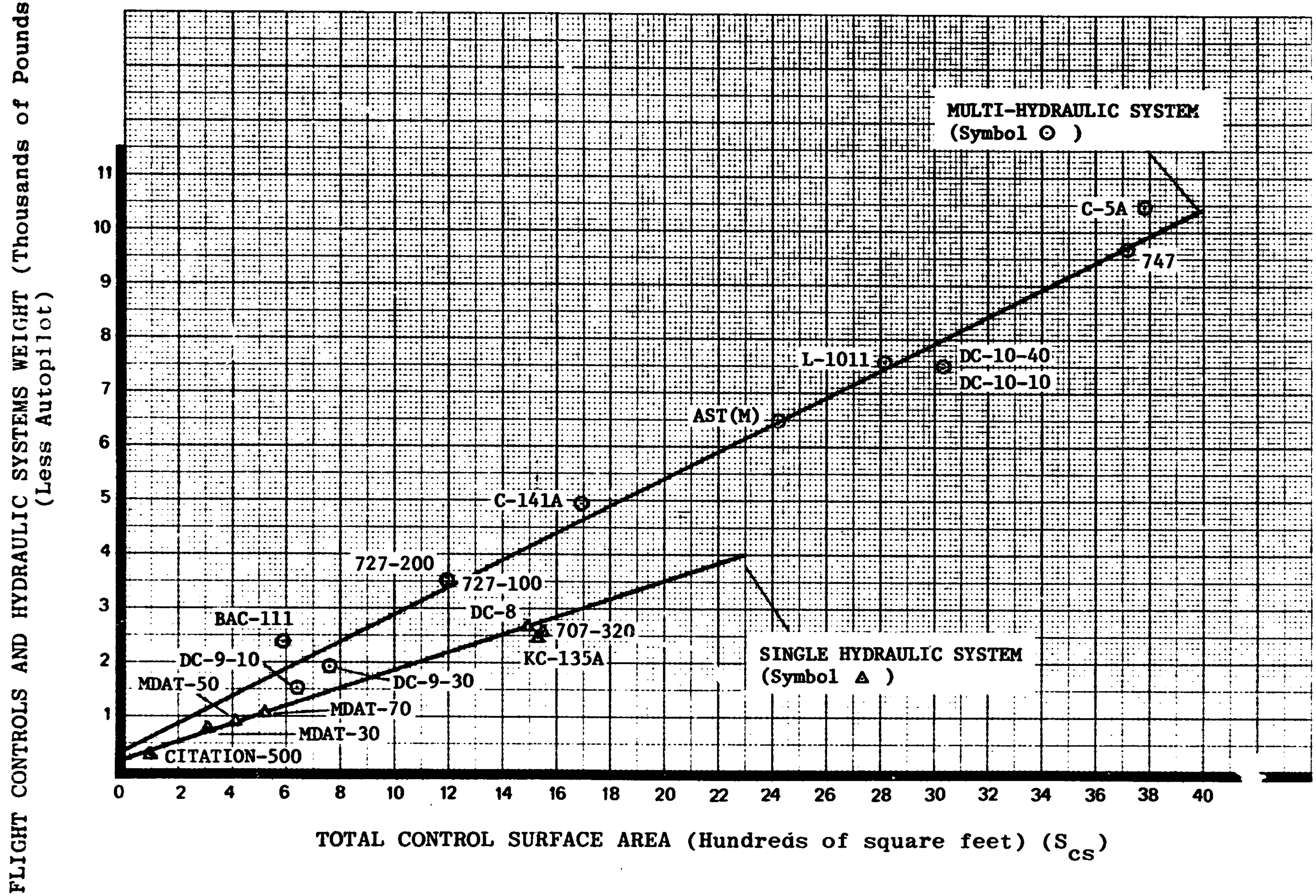
Table 5.12

FLIGHT CONTROLS AND HYDRAULIC SYSTEMS WEIGHT AND DESIGN DATA - MILITARY AIRCRAFT

	Symbol	KC-135	C-141A	C-5A	AST(M)
Weight Data					
Flight Controls and Hydraulics	W_7+W_8	2,465	4,952	10,471	6,498
Flight Controls	W_7	2,000	3,448	6,936	4,668
Hydraulics	W_8	465	1,504	3,535	1,830
Hydraulics as % of Combined		18.9	30.4	33.8	28.2
%MEW		2.5	3.8	3.3	5.7
Design Data					
Flight Controls					
Wing Area	S_w	2,430	3,002	6,200	1,890
Tail Area	S_t	863	899	1,927	1,378
—	$S_w + 1.44S_t$	3,673	4,297	8,975	3,874
Control Surface Area	S_{cs}	1,288	1,689	3,779	2,422
Hydraulics					
Number of Independent Systems		1	2	4	3
Number of Engine Driven Pumps		2	4	8	8

Figure 5.25

FLIGHT CONTROLS AND HYDRAULIC WERs)
(LESS AUTOPILOT)



function of the wing and tail area* in Figure 5.26. The correlation is still good except that the AST(M), which has almost double the control surface area of conventional aircraft, does not correlate well.

The alternate equations are:

$$W_7 + W_8 = 45.0 + 0.269\ (S_w + 1.44\ S_t)^{1.106} \quad \text{Single Hydraulic System}$$

$$W_7 + W_8 = 45.0 + 1.318\ (S_w + 1.44\ S_t) \quad \text{Multi-Hydraulic System } (S_w + 1.44\ S_t) \le 3{,}000$$

$$W_7 + W_8 = 18.7\ (S_w + 1.44\ S_t)^{0.712} - 1{,}620 \quad \text{Multi-Hydraulic System } (S_w + 1.44\ S_t) > 3{,}000$$

Since it may be easier during preliminary design to determine the wing and tail area than the control surface area, the last three equations may be preferred. These are satisfactory except for unusual designs such as a STOL type aircraft.

Separate WERs were developed for the flight control system and the hydraulic system by examining the ratio of the hydraulic system weight to the combined systems weight. This ratio, expressed as a percent, is plotted as a function of control surface area and of wing and tail area in Figures 5.27 and 5.28, respectively. Since there is no clear correlation of these ratios with control surface or wing and tail areas, averages for single and for multi-hydraulic systems are used. For this purpose, non production aircraft (the MDAT series, SCAT-15 and AST(M)) were excluded.

The equations are:

$$W_7 = 0.769\ (W_7 + W_8) \quad \text{Single Hydraulic System}$$

$$W_7 = 0.728\ (W_7 + W_8) \quad \text{Multi-Hydraulic System}$$

$$W_8 = 0.231\ (W_7 + W_8) \quad \text{Single Hydraulic System}$$

$$W_8 = 0.272\ (W_7 + W_8) \quad \text{Multi-Hydraulic System}$$

* The DC-10 area includes only the portion of the vertical tail above the engine.

Figure 5.26

FLIGHT CONTROLS AND HYDRAULIC SYSTEMS WERs
(Less Autopilot Weight)

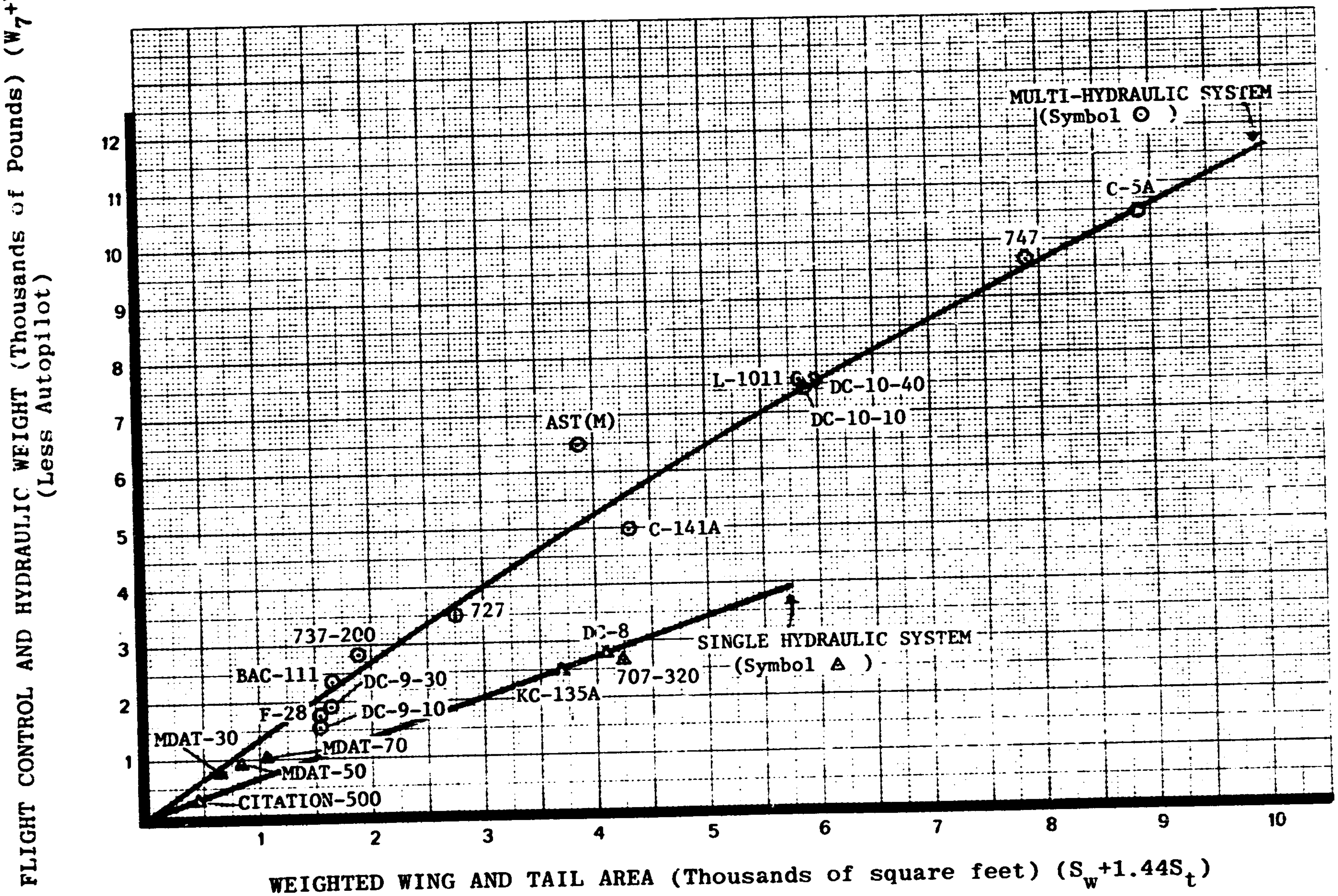


Figure 5.27

HYDRAULICS PERCENT vs. CONTROL SURFACE AREA

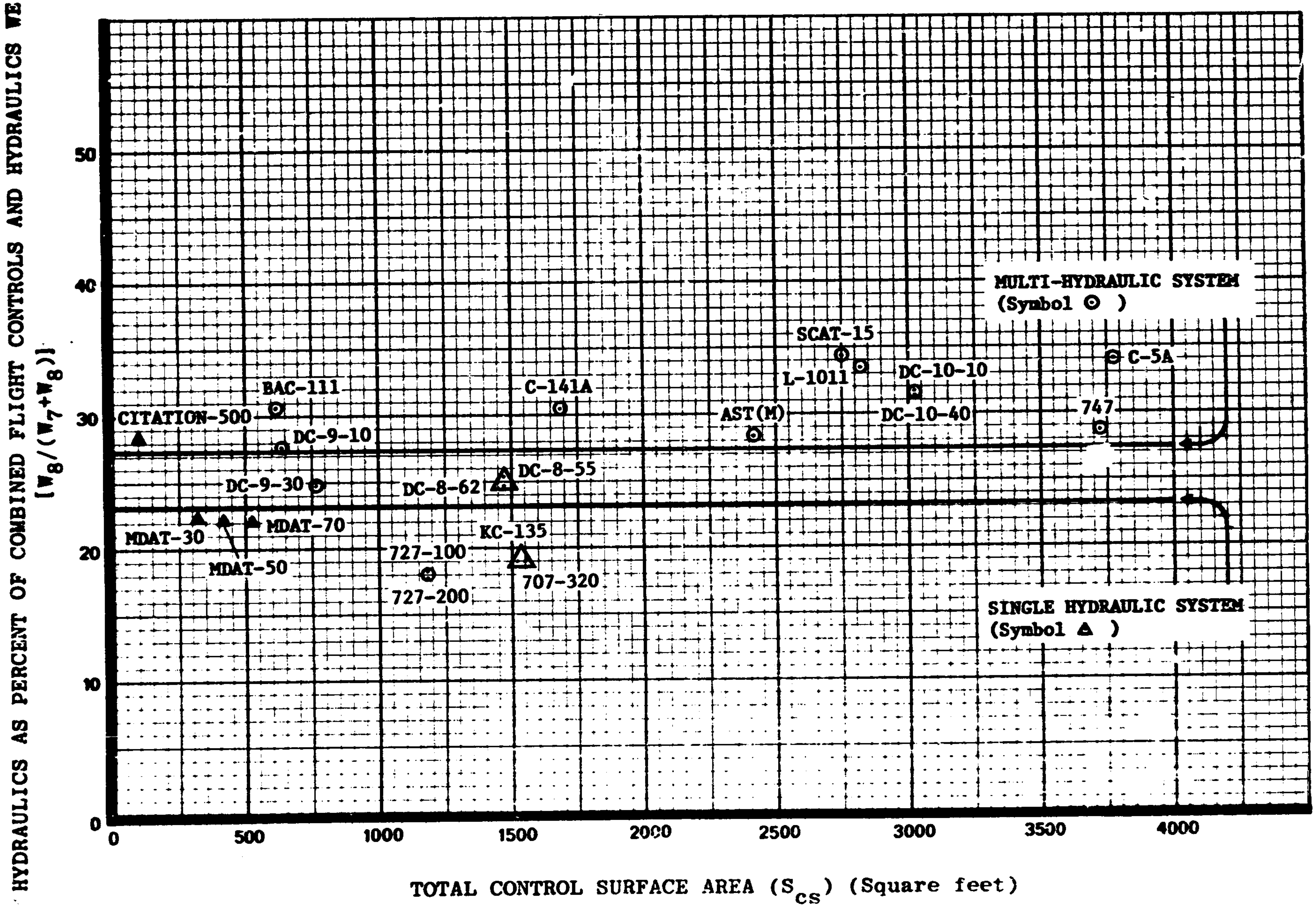
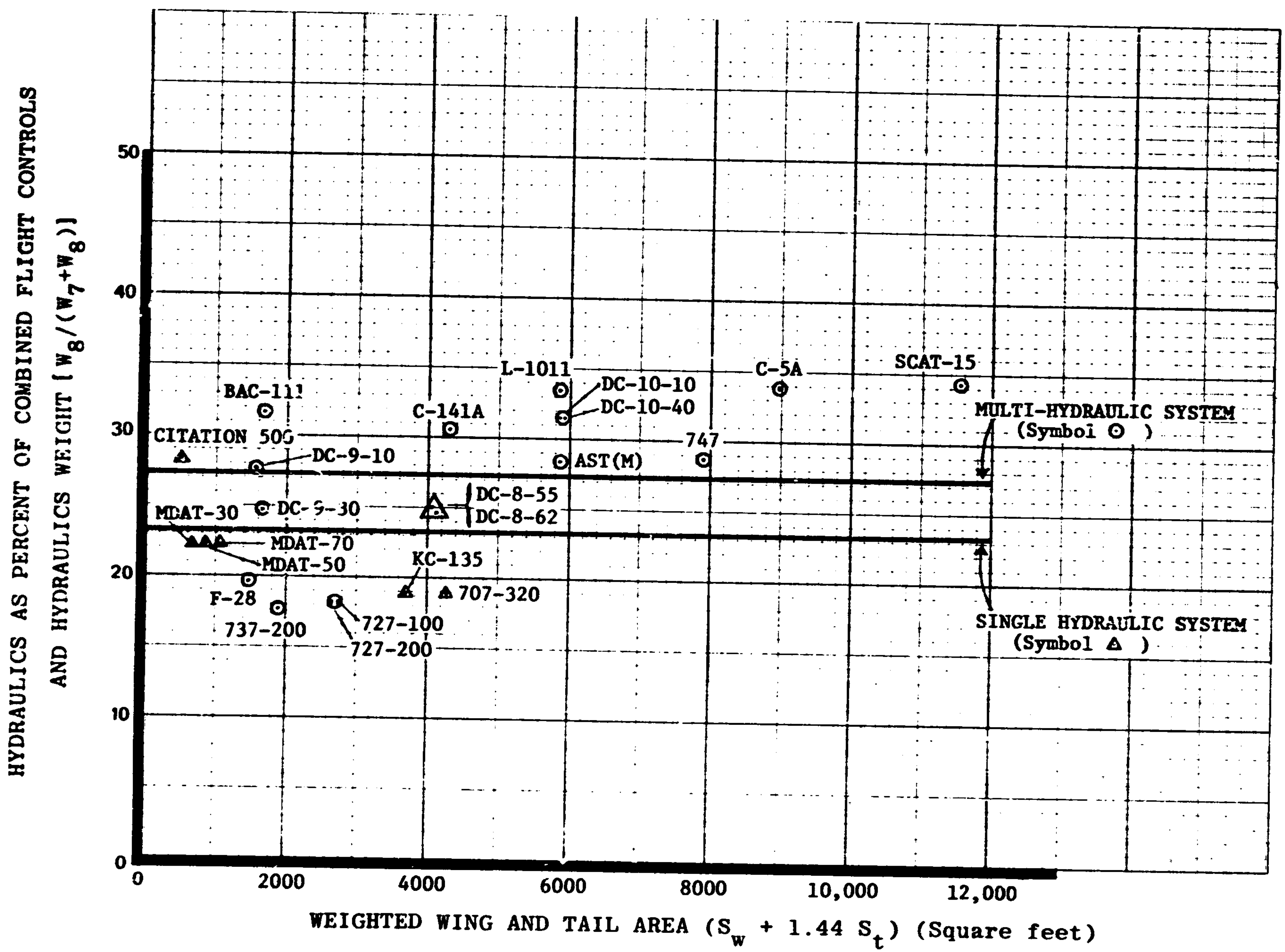


Figure 5.28

HYDRAULICS PERCENT vs. WEIGHTED WING AND TAIL AREA



Emerging Technologies

The flight controls and hydraulic systems would be greatly affected by implementing new, power-by-wire technology. The estimated effect on the total aircraft weight of changing to wire controls or active controls on the DC-9 and DC-10 is shown in Table 5.13. Component weight differences resulting from reduced static stability (RSS), gust load alleviation (GLA) and maneuver load alleviation (MLA) are tabulated. The structural weight increments with RSS represent reductions in tail size, in fuselage bending moments due to a smaller tail, in wing loads due to greater up tail loads for a balanced flight condition and an increase in alighting gear strut length to maintain adequate aircraft rotation for constant field length. The longer strut is required because the wing with RSS is moved forward for balance purposes as a result of the further aft center of gravity limit positions. Additional structural weight is saved because the gust load factor can be reduced and the center-of-pressure of the maneuver wing load can be shifted inboard. Care must be taken that the weight savings with the additions of GLA and MLA are coordinated with other design conditions which are not affected by GLA and MLA but which may become critical before the full advantage of GLA and MLA can be realized.

The DC-10 flight controls are readily adaptable to active control technology since the DC-10 is configured with a four-channel autopilot and full power flight controls. However, the DC-9 flight controls and electrical power system would have to be changed to provide the increased capabilities demanded by all active control functions. Therefore, systems weight penalties to the DC-9 are significant.

Table 5.13

EXAMPLE APPLICATIONS OF ACTIVE CONTROLS

TYPE OF ACTIVE CONTROLS	DC-9-30 REDUCED STATIC STABILITY	DC-9-30 GUST & LOAD ALLEVIATION	DC-9-30 RSS + GLA & MLA	DC-10-30 REDUCED STATIC STABILITY	DC-10-30 GUST & LOAD ALLEVIATION	DC-10-30 RSS + GLA & MLA
Wing	+ 101	- 534	- 433	- 1,347	- 571	- 1,918
Horizontal Tail	- 891	0	- 891	- 5,630	0	- 5,630
Vertical Tail	- 92	0	- 92	- 377	0	- 377
Fuselage	- 280	- 161	- 441	- 2,761	- 207	- 2,968
Landing Gear	+ 178	0	+ 178	+ 1,475	0	+ 1,475
Flight Controls	+ 310	0*	+ 310	- 675	0*	- 675
Engine Pylon	0	- 48	- 48	0	- 260	- 260
Hydraulics	+ 190	0*	+ 190	0	0	0
Electrical	+ 100	0*	+ 100	- 75	0*	- 75
Net Weight Reduction (Lbs. per aircraft)	- 384	- 743	- 1,127	- 9,390	- 1,038	-10,428
MEW	55,450	55,450	55,450	247,079	247,079	247,079
%Savings (per aircraft)	0.7	1.3	2.0	3.8	0.4	4.2

* Would be applicable to GLA & MLA if not already included in RSS.

F. ELECTRICAL SYSTEM

Weight Characteristics

System and component weights of the electrical system are presented in Tables 5.14 and 5.15 for commercial and military aircraft, respectively. The miscellaneous equipment and wiring weight includes racks, shelves and connection wiring for operational equipment. For the Douglas commercial aircraft, the miscellaneous equipment is included in the AC distribution system.

Weight Estimating Relationships

The electrical system weight was found to correlate well with the number of passengers (data from Table 5.1) for commercial transports and with the body wetted area (data from Table 5.2) for military transports. These data are plotted in Figures 5.29 and 5.30. The commercial transport data were correlated without the 707, 747 or SCAT-15. The lighter 747 weight can be attributed to the dual system low intensity cabin lighting system and to the utilization of four engine driven 60 KVA generators. By contrast the heavier DC-10 weight can be attributed to the triple high intensity lighting system, which includes integral air conditioning plenium/ lighting supports and three 90 KVA engine driven generators. The difference between the 747 and the DC-10 lighting system weights is due to different design philosophies and weight allocation for the support/pleniums. The different generator capacities on the 747 and DC-10 are because of different engine out and dispatchability design requirements. Sufficient data were not available to determine why the 707 and SCAT-15 were high.

The military transport data from Table 5.15 were supplemented with data for small military transports (C-1A, C-119F, C-123B, DHC-6 and AC-1) in Figure 5.30. This figure indicates different electrical system WERs for small and for medium and large military transports.

Table 5.14

ELECTRICAL SYSTEM WEIGHT DATA - COMMERCIAL AIRCRAFT

	Symbol	Citation-500	MDAT-30	MDAT-50	F-28	MDAT-70	DC-9-10	BAC-111	DC-9-30	737-200
Electrical System Weight	W_9	361	617	825	953	1,040	1,631	1,610	1,715	2,156
AC Power System		38	302	405	467	510	1,011	627	1,038	—
Generators and Installation		—	233	313	361	394	169	169	169	—
Constant Speed Drives		—	—	—		—	182	239	181	—
Power Conversion Equipment		38	—	—	—	—	4	—	43	—
Power Distribution and Controls		—	69	92	106	116	656	219	645	—
DC Power System		301	128	170	197	215	258	228	259	—
Generators and Installation		Part of Eng. Starter Wt.	—	—	197	—	—	—	—	—
Batteries and Installation		82	54	73	84	92	125	227	125	—
Power Conversion Equipment		—	3	3	4	4	73	—	51	—
Power Distribution and Controls		219	71	94	109	119	60	1	83	—
Lights and Signal Devices		22	139	186	215	234	356	258	418	—
Interior Lights		9	83	111	128	140	228	90	277	—
Exterior Lights		4	17	23	26	28	46	23	60	—
Landing Lights		3	22	29	34	37	57	46	56	—
Signal and Misc. Lights		6	17	23	27	29	25	99	25	—
Misc. Equipment and Supports		—	48	64	74	81	6	497	—	—
AC System		—	—	—	—	—	—	497	—	—
DC System		—	48	64	74	81	6	—	—	—
%MEW		5.7	3.0	3.1	2.8	3.0	3.4	3.1	3.1	3.8

Table 5.14 (Continued)

ELECTRICAL SYSTEM WEIGHT DATA - COMMERCIAL AIRCRAFT

	Symbol	727-100	727-200	707-320	DC-8-55	DC-8-62	DC-10-10	L-1011	DC-10-40	747	SCAT-15
Electrical System Weight	W_9	2,988	2,844	3,944	2,414	2,752	5,366	5,490	5,293	5,305	6,002
AC Power System		2,142	2,205	3,385	1,734	1,996	3,231	2,669	3,199	2,930	3,719
Generators and Installation		259	245	} 823	221	310	312	167	312	321	368
Constant Speed Drives		339	233		483	357	338	332	360	320	368
Power Conversion Equipment		64	41	163	40	23	68	20	64	54	50
Power Distribution and Controls		1,480	1,686	2,399	990	1,306	2,513	2,150	2,463	2,235	2,933
DC Power System		67	140	17	114	92	321	339	327	320	836
Generators and Installation		—	—	—	—	—	—	—	—	—	—
Batteries and Installation		—	—	17	16	16	133	197	134	84	100
Power Conversion Equipment		11	71	—	70	70	58	52	64	18	230
Power Distribution and Controls		56	69	—	28	6	130	90	129	218	506
Lights and Signal Devices		400	371	238	566	664	1,814	2,147	1,767	2,055	1,127
Interior Lights		270	208	169	450	527	1,597	1,858	1,542	1,941	1,001
Exterior Lights		32	44	22	47	53	120	128	121	30	75
Landing Lights		61	72	36	58	73	50	107	57	54	41
Signal and Misc. Lights		37	47	11	11	11	47	54	47	30	10
Misc. Equipment and Supports		379	128	304	—	—	—	335	—	—	320
AC System		379	128	303	—	—	—	335	—	—	320
DC System		—	—	1	—	—	—	—	—	—	—
ΣMEW		3.5	3.0	3.2	1.8	2.0	2.4	2.4	2.1	1.6	2.0

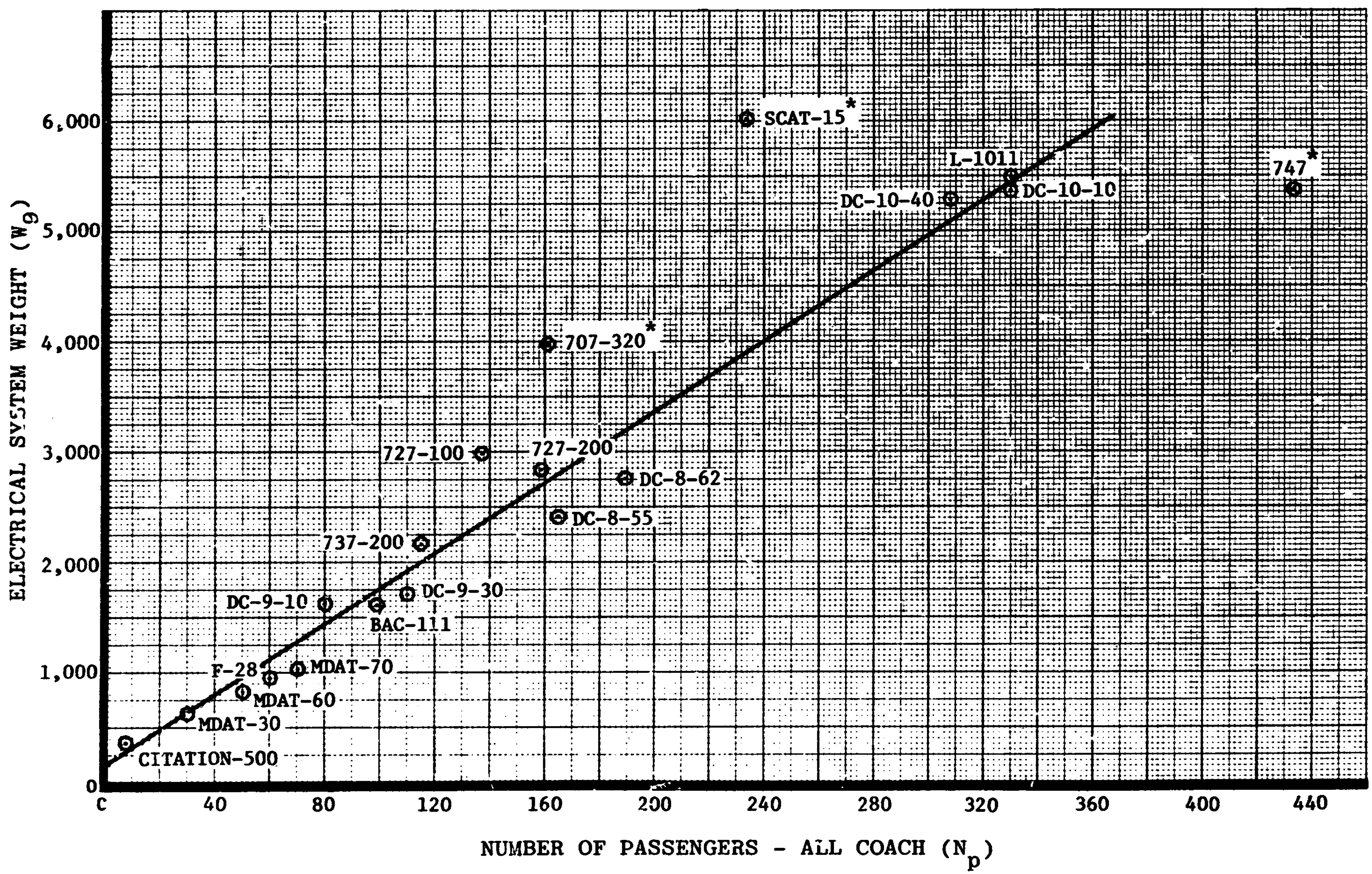
Table 5.15

ELECTRICAL SYSTEM WEIGHT DATA - MILITARY AIRCRAFT

	Symbol	C-130A	KC-135A	C-13'	C-141A	C-5A	AST(M)
Electrical System Weight	W_9	1,680	2,333	2,526	3,015	3,300	2,058
AC Power System		514	1,708	1,341	2,312	1,984	1,495
Generators and Installation		210	289	242	377	304	354
Constant Speed Drives		—	284	—	438	354	76
Power Conversion Equipment		2	137	13	24	26	—
Power Distribution and Controls		302	998	1,086	1,473	1,300	1,065
DC Power System		805	447	530	221	208	355
Generators and Installation		207	—	51	—	—	—
Batteries and Installation		110	68	89	44	37	135
Power Conversion Equipment		93	—	93	70	67	114
Power Distribution and Controls		395	379	297	107	104	106
Lights and Signal Devices		109	85	415	427	558	218
Interior Lights		63	31	251	234	364	114
Exterior Lights		22	27	43	81	71	48
Landing Lights		24	19	57	34	45	38
Signal and Misc. Lights		—	8	64	78	78	18
Misc. Equipment and Supports		252	93	240	55	550	—
AC System		87	86	152	55	540	—
DC System		165	7	88	—	10	—
ZMEW		2.8	2.5	2.1	2.3	1.0	1.8

Figure 5.29

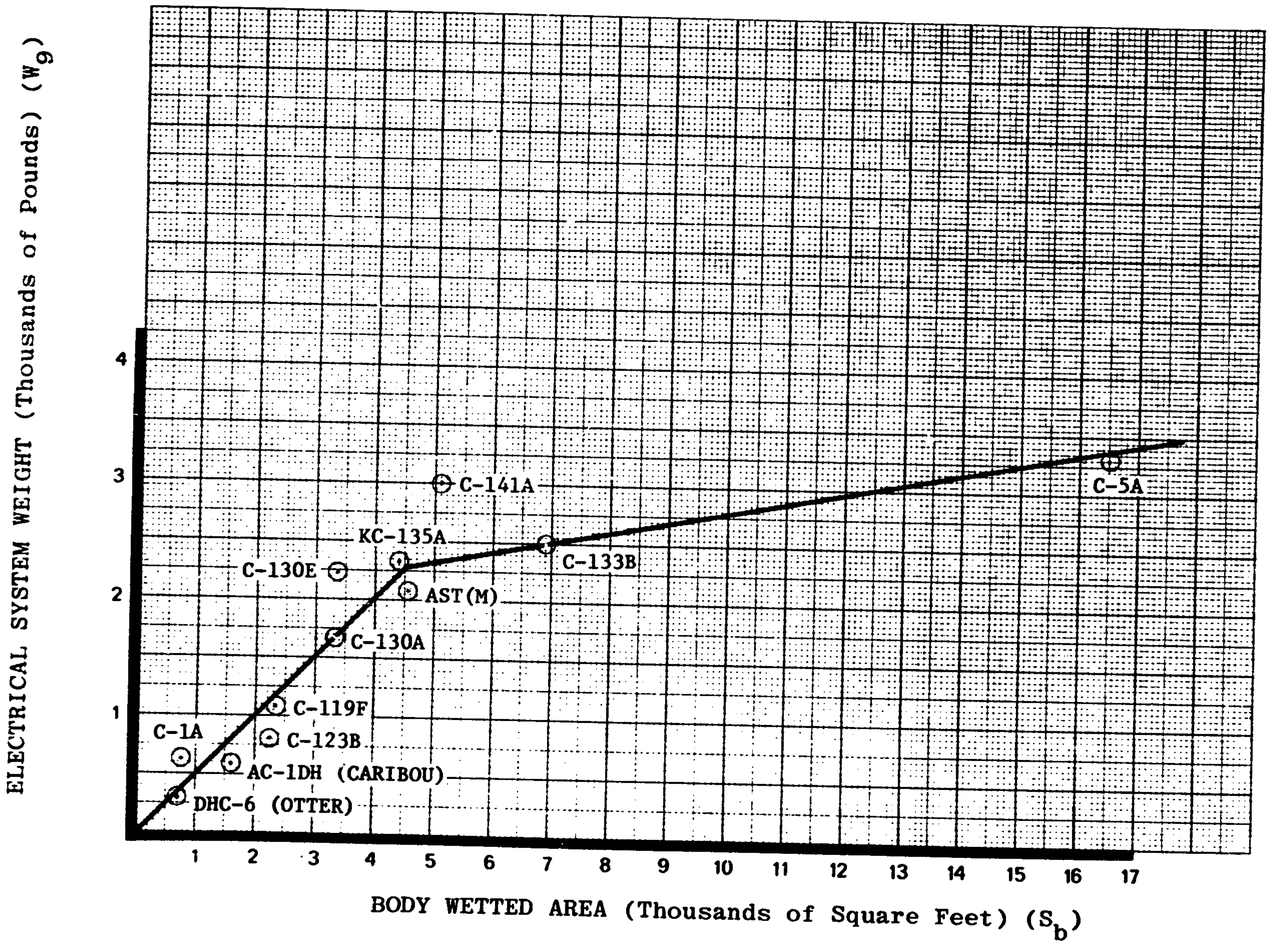
ELECTRICAL SYSTEM WER - COMMERCIAL AIRCRAFT



*Excluded from Regression

Figure 5.30

ELECTRICAL SYSTEM WER - MILITARY AIRCRAFT



The equations are:

$W_9 = 16.2\ N_p + 110$	Commercial
$W_9 = 0.508\ S_b$	Military $S_b \leq 4,500$
$W_9 = 0.0919\ S_b + 1,870$	Military $S_b > 4,500$

G. PNEUMATIC, AIR CONDITIONING AND AUXILIARY POWER SYSTEMS

The pneumatic, air conditioning and auxiliary power systems are combined for weight correlation purposes because of different functional weight allocations and system interpretation among aircraft manufacturers. Significant portions of the aircraft pneumatic and auxiliary power systems are designed by ground cooling requirements with a full passenger load for commercial aircraft and by engine start requirements for military aircraft. The ice protection systems are considered separately because of significant differences in anti-icing requirements among the aircraft (e.g., not all aircraft have wing or tail anti-icing provisions).

Because of the interdependence among these systems, it is difficult to develop meaningful WERs for the separate systems. However, separate correlations were done with and without the auxiliary power system. This gave equations for the auxiliary power system alone (the difference between the two correlations) and the combined air conditioning and pneumatic systems. The latter equation was then divided between air conditioning and pneumatic based on approximate weight percentages.

Weight Characteristics

Weight breakdowns for the pneumatic system are presented in Tables 5.16 and 5.17 for commercial and military aircraft, respectively. Weight breakdowns for the air conditioning system are presented in Tables 5.18 and 5.19 for commercial and military aircraft, respectively. Auxiliary power system weight breakdowns are presented in Tables 5.20 and 5.21 for commercial and military aircraft, respectively. Aircraft without auxiliary power systems include DC-8, 707, 727-100 and KC-135.

Weight Estimating Relationships

Combined systems weights with and without the auxiliary power system were found to correlate reasonably well with the number of passengers (data from Table 5.1) for commercial transports and with body wetted area (data from Table 5.2) for military transports. Data are plotted in Figures 5.31 and 5.32. The DC-8 and C-133 weights are exceptionally heavy. The

Table 5.16

PNEUMATIC SYSTEM WEIGHT DATA - COMMERCIAL AIRCRAFT

	Symbol	Citation-500	MDAT-30	MDAT-50	F-28	MDAT-70	DC-9-10	BAC-111	DC-9-30	737-200
Pneumatic System	W_{10}	48	86	100	64	115	263	656	278	330
Heat Exchangers		—	—	—	—	—	—	132	—	70
Valves		10	13	15	—	17	40	109	38	38
Controls		—	8	9	—	10	23	61	24	—
Ducting & Supports		32	65	76	60	88	200	317	212	222
Misc. Equipment & Supports		6	—	—	4	—	—	37	4	—
%MEW		0.8	0.4	0.4	0.2	0.3	0.5	1.3	0.5	0.3

Table 5.16 (Continued)

PNEUMATIC SYSTEM WEIGHT DATA - COMMERCIAL AIRCRAFT

	Symbol	727-100	727-200	707-320	DC-8-55	DC-8-62	DC-10-10	L-1011	DC-10-40	747	SCAT-15
Pneumatic System	W_{10}	427	458	1,059	1,570	1,057	1,787	1,870	1,957	2,287	5,070
Heat Exchangers		72	83	197	172	88	161	—	180	498	3,073
Valves		114	104	241	187	200	250	469	260	246	—
Controls		29	20	—	13	4	106	80	102	19	—
Du-ting & Supports		212	251	621	1,198	765	1,270	1,305	1,415	1,524	1,997
Misc. Equipment & Supports		—	—	—	—	—	—	16	—	—	—
ZMEW		0.5	0.5	0.8	1.2	0.8	0.8	0.8	0.8	0.7	1.7

Table 5.17

PNEUMATIC SYSTEM WEIGHT DATA - MILITARY AIRCRAFT

	Symbol	C-130A	KC-135A	C-133B	C-141A	C-5A	AST(M)
Pneumatic System	W_{10}	211	595	871	659	782	635
Heat Exchangers		—	104	—	—	—	80
Valves		—	93	48	44	116	172
Controls		25	—	25	45	62	29
Ducting & Supports		176	216	798	524	565	297
Misc. Equipment & Supports		10	182	—	46	39	57
%MEW		0.3	0.6	0.7	0.5	0.2	0.6

Table 5.18

AIR CONDITIONING SYSTEM WEIGHT DATA - COMMERCIAL AIRCRAFT

	Symbol	Citation-500	MDAT-30	MDAT-50	F-28	MDAT-70	DC-9-10	BAC-111	DC-9-30	737-200
Air Conditioning	W_{11}	157	325	435	520	550	1,016	1,062	1,110	1,084
Refrigeration System		50	106	143	170	180	419	316	447	98
Aircycle Unit/Compressor/Fans		17	74	100	—	126	142	135	144	98
Heat Exchangers		10			119		131	118	147	—
Water Separators		3	9	12	14	15	13	—	13	—
Valves, Regulators, & Misc.		20	23	31	37	39	133	63	143	—
Cargo Heat/Cooling System		--	--	—	—	--	17	106	22	—
Distribution System		42	145	194	232	245	447	495	507	860
Controls		2	14	18	22	23	381	33	39	—
Pressure Control System		59	50	67	80	85	95	55	95	79
Valves & Regulators		16	—	—	—	—	74	54	74	—
Seals, Plumbing, & Misc.		43	—	—	—	—	—	13	—	—
Controls		--	--	—	—	—	21	8	21	—
Misc. Equipment & Supports		4	10	13	16	17	—	57	—	47
ZMEW		2.5	1.6	1.6	1.6	1.6	2.1	2.1	2.0	1.9

Table 5.18 (Continued)

AIR CONDITIONING SYSTEM WEIGHT DATA - COMMERCIAL AIRCRAFT

	Symbol	727-100	727-200	707-320	DC-8-55	DC-8-62	DC-10-10	L-1011	DC-10-40	747	SCAT-15
Air Conditioning	W_{11}	1,526	1,802	1,602	2,388	2,296	2,386	3,344	2,527	3,631	2,820
Refrigeration System		556	619	494	1,250	1,266	1,084	957	1,084	1,761	--
Aircycle Unit/Compressor/Fans		40	104	471	814	849	437	216	437	315	--
Heat Exchangers		189	230	--	109	104	--	364	--	253	--
Water Separators		22	22	23	--	--	54	47	55	65	--
Valves, Regulators, & Misc.		305	263	--	327	313	593	330	592	1,088	--
Cargo Heat/Cooling System		--	24	--	165	88	150	218	213	54	206
Distribution System		749	855	972	762	738	874	1,786	941	1,389	2,156
Controls		93	160	--	--	--	30	184	47	295	79
Pressure Control System		84	88	136	211	204	248	199	242	135	208
Valves & Regulators		42	62	--	96	93	196	103	188	91	--
Seals, Plumbing, & Misc.		24	--	--	92	90	--	70	--	3	--
Controls		18	26	--	23	21	52	26	54	41	--
Misc. Equipment & Supports		44	56	--	--	--	--	--	--	--	171
ZMEW		1.8	1.9	1.3	1.8	1.7	1.1	1.5	1.0	1.1	0.9

Table 5.19

AIR CONDITIONING SYSTEM WEIGHT DATA - MILITARY AIRCRAFT

	Symbol	C-130A	KC-135A	C-133B	C-141A	C-5A	AST(M)
Air Conditioning	W_{11}	1,108	743	1,746	1,547	2,602	906
Refrigeration System		142	59	448	509	498	273
Aircycle Unit/Compressor/Fans		98	34	448	25	146	25
Heat Exchangers		--	--	--	293	195	133
Water Separators		14	12	--	25	32	25
Valves, Regulators, & Misc.		30	13	--	166	125	90
Cargo Heat/Cooling System		--	--	--	--	81	124
Distribution System		532	465	857	537	1,329	377
Controls		35	--	1	59	95	46
Pressure Control System		269	92	436	346	116	86
Valves & Regulators		32	92	--	42	78	--
Seals, Plumbing, & Misc.		232	--	253	268	9	--
Controls		5	--	183	36	29	--
Misc. Equipment & Supports		130	127	4	96	482	--
ZMEW		1.8	0.8	1.4	1.2	0.8	0.8

Table 5.20

AUXILIARY POWER SYSTEM WEIGHT DATA - COMMERCIAL AIRCRAFT

	Symbol	Citation-500	MDAT-30	MDAT-50	F-28	MDAT-70	DC-9-10	BAC-111	DC-9-30	737-200	727-200	DC-10-10	L-1011	DC-10-40	747
Auxiliary Power	W_{13}	—	343	400	320	460	805	719	817	855	849	1,589	1,202	1,592	1,797
Engine		—	138	160	150	184	323	319	322	319	320	597	724	597	609
Engine Mounts		—	7	9	9	10	17	34	18	—	7	16	14	16	27
Air Induction		—	22	26	34	30	52	23	52	69	34	115	26	112	118
Exhaust System		—	25	29	33	34	59	22	59	65	68	211	112	211	102
Cooling System		—	6	7	15	8	13	4	13	16	—	36	27	36	15
Lube System		—	—	—	—	—	—	2	—	—	12	—	24	—	—
Fuel System		—	16	18	9	21	37	28	36	39	8	28	19	28	87
Controls		—	35	41	2	47	82	55	89	—	57	37	11	85	41
Start System		—	7	8	34	9	16	—	15	—	—	55	30	56	137
Enclosure and Insulation		—	22	26	20	30	52	39	52	73	87	200	58	200	131
Electric Gen. & Circuitry		—	57	66	—	75	133	155	138	205	218	201	136	205	428
Fire Extinguishing System		—	5	6	14	7	12	38	13	18	15	18	—	20	72
Pneumatic System		—	3	4	—	5	9	—	10	50	27	25	21	26	30
%MEW		—	1.7	1.5	1.0	1.3	1.7	1.4	1.5	1.5	0.9	0.7	0.5	0.6	0.5

Table 5.21

AUXILIARY POWER SYSTEM WEIGHT DATA - MILITARY AIRCRAFT

	System	C-130A	C-133B	C-141A	C-5A	AST(M)
Auxiliary Power	W_{13}	482	1,584	635	1,067	651
Engine		181	737	254	399	200
Engine Mounts		24	28	40	18	9
Air Induction		8	185	17	45	22
Exhaust System		—	50	29	40	20
Cooling System		—	9	13	11	6
Lube System		21	—	12	11	6
Fuel System		20	61	7	22	15
Controls		14	139	24	38	75
Start System		—	—	102	157	80
Enclosure and Insulation		49	121	49	46	70
Electric Gen. & Circuitry		113	178	88	280	125
Fire Extinguishing System		—	—	—	—	—
Pneumatic System		52	76	—	—	23
ZMEW		0.8	1.3	0.5	0.3	0.6

Figure 5.31

PNEUMATIC, AIRCONDITIONING AND AUXILIARY POWER WERs - COMMERCIAL AIRCRAFT

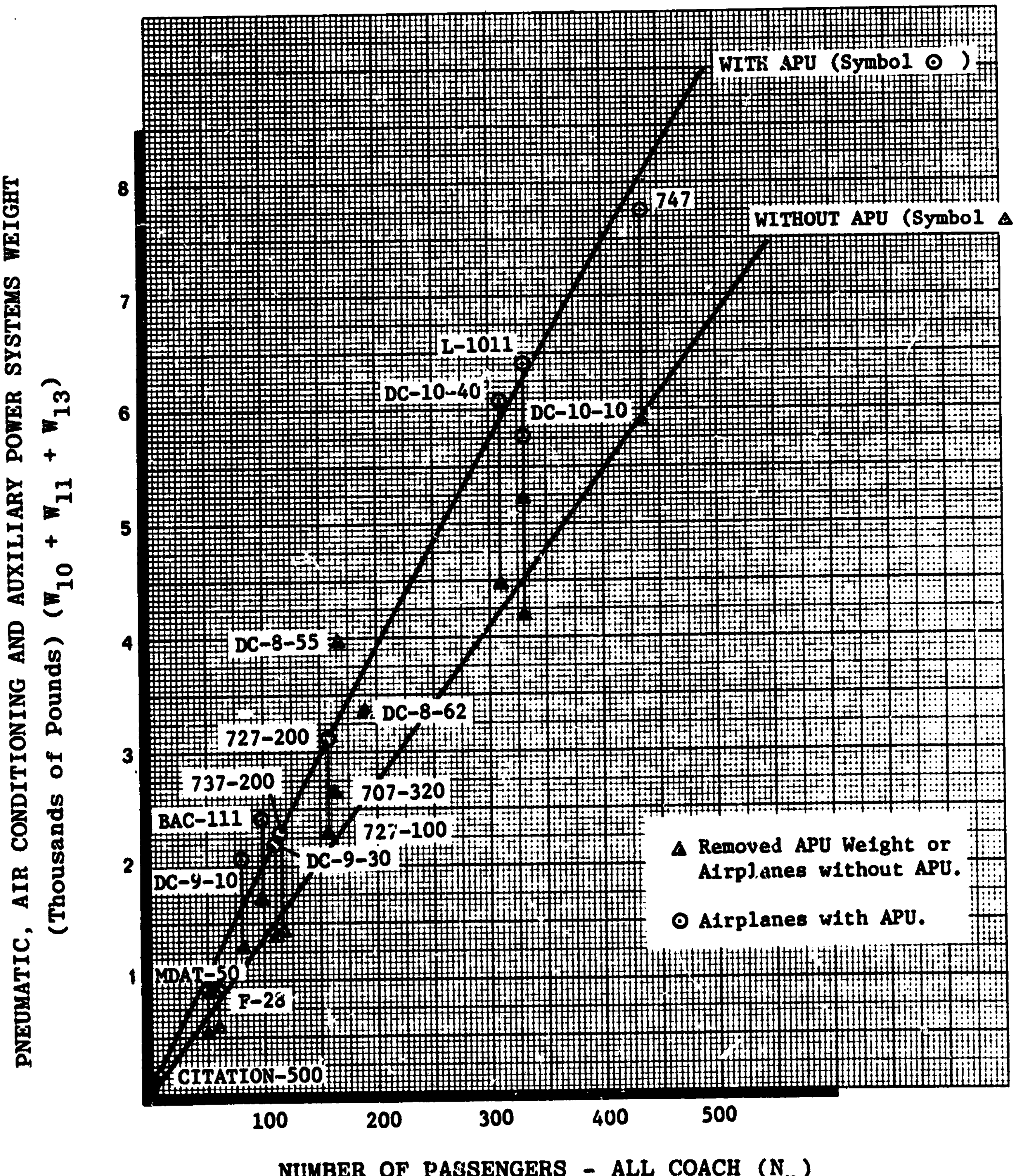
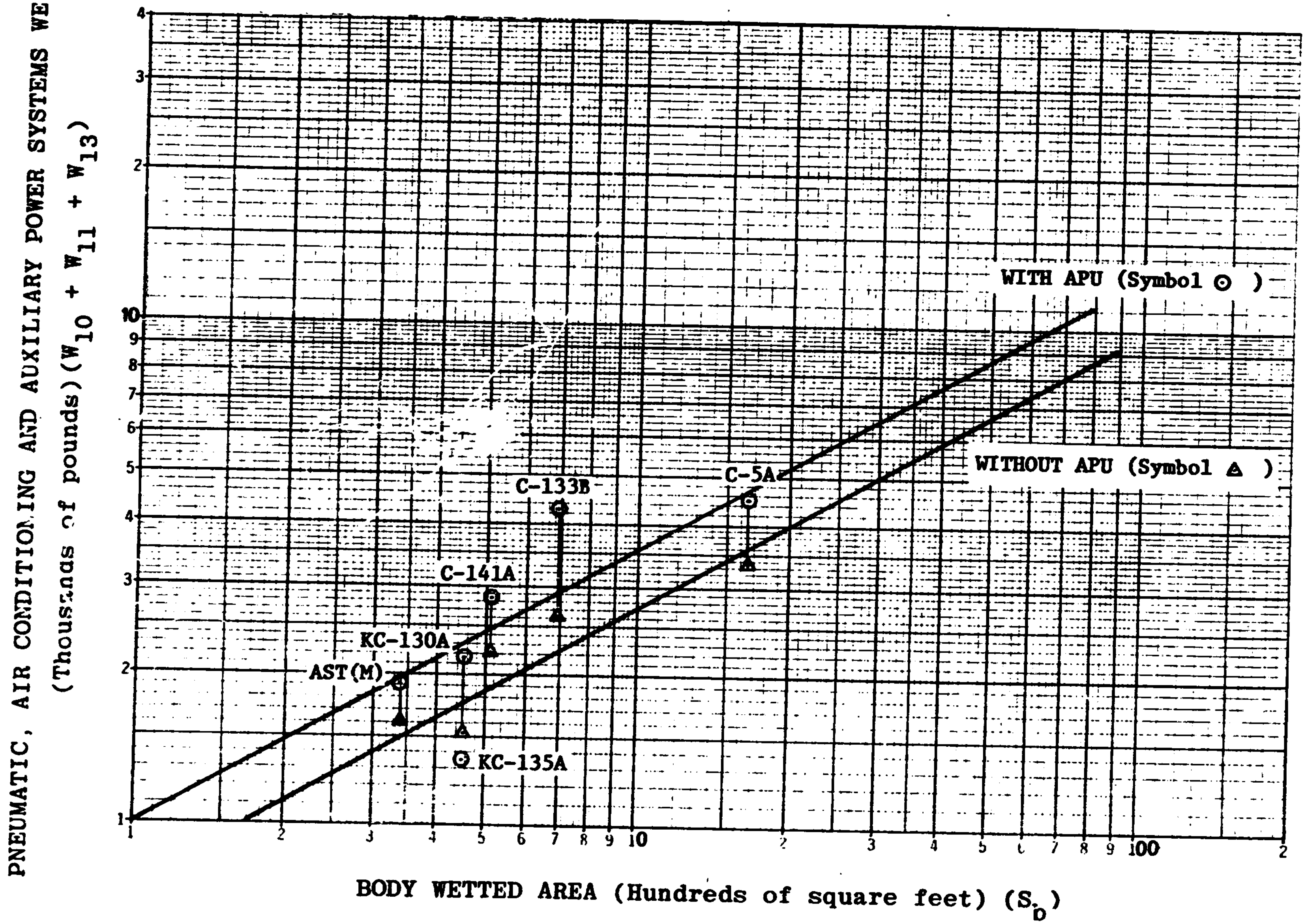


Figure 5.32

PNEUMATIC, AIR CONDITIONING AND AUXILIARY POWER WERs - MILITARY AIRCRAFT



pneumatic system on the DC-8-55 uses steel ducting and the DC-8 air conditioning system uses a freon cooling system which requires an evaporator, condenser and an extra compressor. The C-133B APU weight is very high due to the use of two gas turbine units to provide utility hydraulic and electrical power in addition to providing primary bleed air for air conditioning and pneumatic systems. Therefore, the DC-8 and C-133 were excluded from the correlations.

The equations are:

$$\left.\begin{aligned} W_{10} + W_{11} + W_{13} &= 26.2\ N_p^{0.944} \\ W_{10} + W_{11} &= 13.6\ N_p \end{aligned}\right\} \quad \text{Commercial}$$

$$\left.\begin{aligned} W_{10} + W_{11} + W_{13} &= 23.4\ S_b^{0.545} \\ W_{10} + W_{11} &= 15.6\ S_b^{0.560} \end{aligned}\right\} \quad \text{Military}$$

The auxiliary power system WERs were obtained by subtraction of the above equations. They are:

$$W_{13} = 26.2\ N_p^{0.944} - 13.6\ N_p \qquad \text{Commercial}$$

$$W_{13} = 23.4\ S_b^{0.545} - 15.6\ S_b^{0.560} \qquad \text{Military}$$

Separate WERs were developed for the air conditioning system and pneumatic system by examining the ratio of the pneumatic system weight to the combined systems weight. This ratio, expressed as a percent, is plotted as a function of N_p and S_b in Figures 5.33 and 5.34, respectively. Since there is no clear correlation of these ratios with N_p and S_b, an average is used. The average for commercial aircraft is 28 percent and for military aircraft is 31 percent. The average for all aircraft is 29 percent. Therefore, the equations are:

$$W_{10} = 0.290\ (W_{10} + W_{11})$$

$$W_{11} = 0.710\ (W_{10} + W_{11})$$

Figure 5.33

PNEUMATIC PERCENT vs. NUMBER OF PASSENGERS

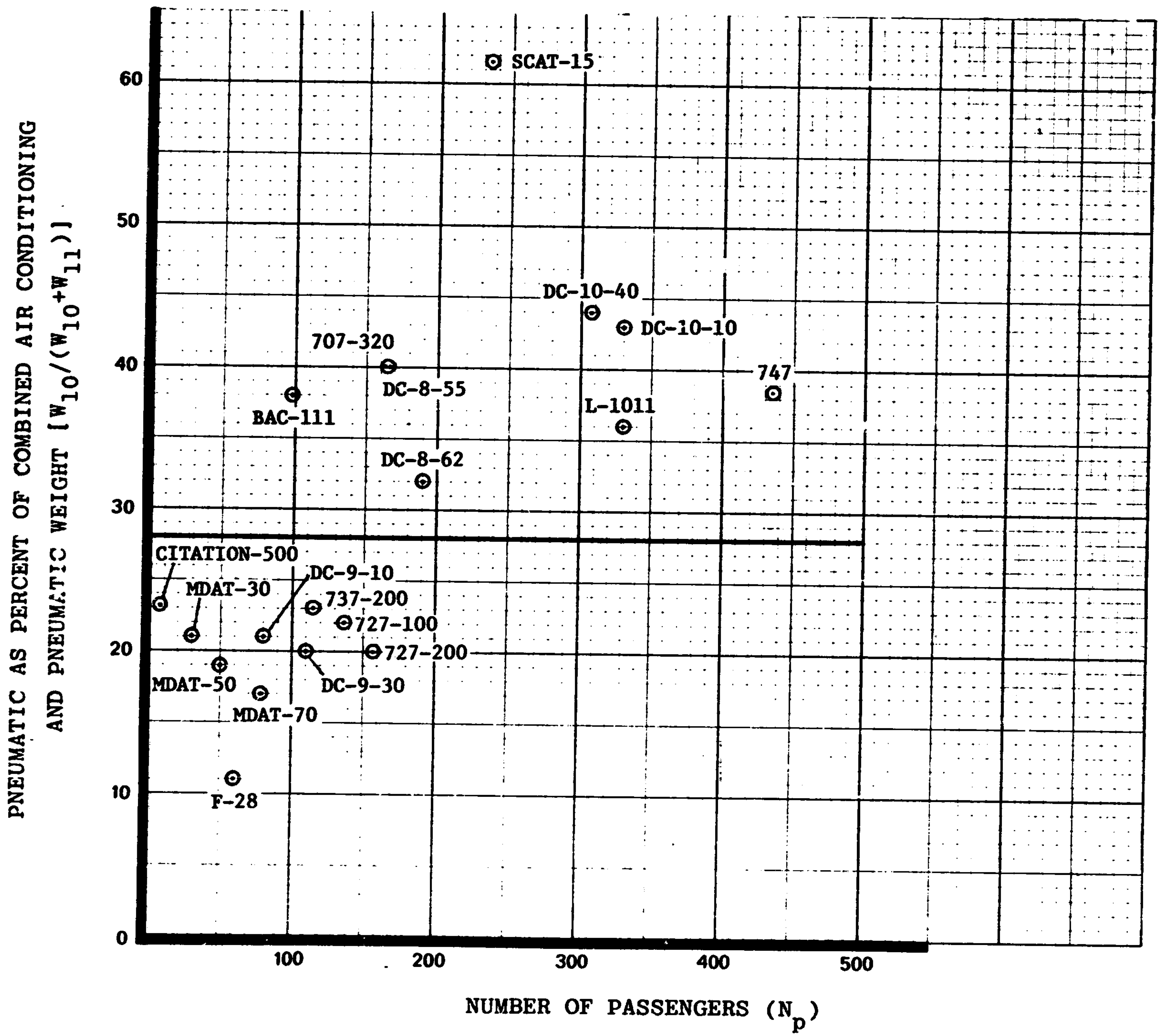
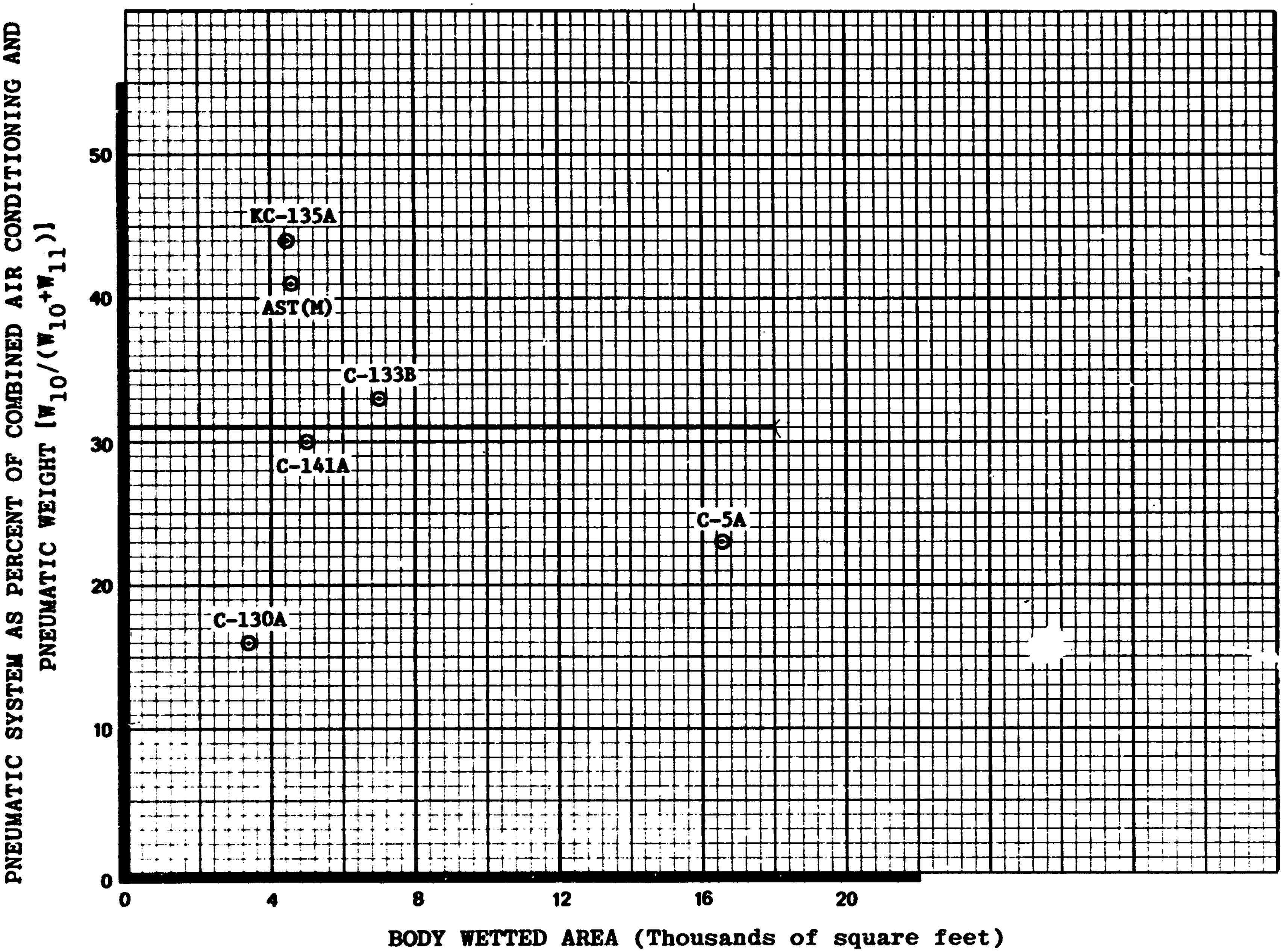


Figure 5.34

PNEUMATIC PERCENT vs. BODY WETTED AREA



H. ANTI-ICING SYSTEM

Weight and Design Characteristics

Anti-icing system weight breakdowns are presented in Tables 5.22 and 5.23 for commercial and military transports, respectively. Weights are tabulated by wing, tail, air induction (nacelle) and miscellaneous ice protection functions.

There are five major configuration differences among anti-icing systems:

- aircraft with air induction (nacelle) anti-icing only,
- aircraft with nacelle and wing but without tail anti-icing,
- wing mounted turbofan or jet engines with tail anti-icing,
- fuselage and/or tail mounted turbofan engines with tail anti-icing, and
- wing mounted turboprop engines with tail anti-icing

There are minor configuration differences within these categories. For example, both the KC-135 and 707 have electrically rather than pneumatically anti-iced tail surfaces. There are also differences between aircraft in what is included in the anti-icing system. For example, the 707 anti-icing weight includes 166 pounds of wiring and controls in the tail, but the KC-135 includes only 20 pounds.

Weight Estimating Relationships

Because of the many differences in anti-icing systems, weight correlations are difficult. Separate correlations were tried for the five major configurations mentioned above using wing area. The choice of wing area is based on the fact that most aircraft have wing anti-icing requirements. However, wing area is also an indicator of aircraft size and is, therefore, an indicator of the general size of duct runs. Anti-icing weights are shown as a function of wing area (S_W) in Figure 5.35. There is much scatter in the data even for the same configuration. For example, the weight difference between the DC-10-10 and DC-10-40 is mainly in the air induction system because of design requirements peculiar to the CF-6 and JT9D engine installations, respectively.

Table 5.22

ANTI-ICING SYSTEM WEIGHT DATA - COMMERCIAL AIRCRAFT

	Symbol	Citation-500	MDAT-30	MDAT-50	F-28	MDAT-70	DC-9-10	BAC-111	DC-9-30	737-200
Anti-Icing	W_{12}	101	384	448	520	511	472	234	474	113
Ducting, Valves, Elect. Heaters, & Insulation		49	283	329	403	375	347	136*	342	113
Wing		15	150	175	334	199	184	91*	209	77
Tail		—	89	104	55	119	110	45	80	—
Air Induction		28	43	50	12	57	53	—	53	36
Miscellaneous		6	—	—	2	—	—	—	—	—
Controls, Wiring, Switches, Plumbing		51	77	90	98	102	96	98	102	—
Wing		9	8	12	47	16	12	14	16	—
Tail		—	7	10	10	13	8	—	8	—
Air Induction		—	7	11	4	15	9	—	11	—
Windshield		4	22	22	36	22	27	31	27	—
Rain Repellent/Windshield Wipers		38	22	22	—	22	27	45	27	—
Miscellaneous		—	11	13	1	14	13	8	13	—
Supports and Attach		1	25	29	19	34	29	—	30	—
Wing		—	12	14	3	16	13	—	13	—
Tail		—	7	8	7	9	8	—	8	—
Fuselage		1	—	—	2	—	—	—	1	—
Nacelle		—	6	7	7	9	8	—	8	—
%MEW		1.6	1.9	1.7	1.6	1.5	1.0	0.5	1.0	0.2

* Anti-ice inner skin weight part of loading edge weight.

Table 5.22 (Continued)

ANTI-ICING SYSTEM WEIGHT DATA - COMMERCIAL AIRCRAFT

	Symbol	727-100	727-200	707-320	DC-8-55	DC-8-62	DC-10-10	L-1011	DC-10-40	747*	SCAT-15
Anti-Icing	W_{12}	639	666	626	794	673	416	296	555	413	210
Ducting, Valves, Elect. Heaters, & Insulation		378	385	413	572	477	275	232	383	245	69
Wing		153	156	204	211	233	170	74	178	—	—
Tail		4	4	47	258	189	—	—	—	—	—
Air Induction		63	81	162	103	55	105	145	205	245	69
Miscellaneous		158	144	—	—	—	—	13	—	—	—
Controls, Wiring, Switches, Plumbing		160	190	166	138	122	112	41	125	168	141
Wing		—	—	—	22	11	3	15	5	—	—
Tail		—	—	166	1	2	—	—	—	—	—
Air Induction		19	8	—	39	31	1	16	8	39	12
Windshield		—	—	—	41	—	46	4	49	62	32
Rain Repellent/Windshield Wipers		26	38	—	31	71	57	—	57	44	97
Miscellaneous		115	144	—	4	7	5	6	6	23	—
Supports and Attach		101	91	47	84	74	29	23	47	—	—
Wing		47	43	25	8	7	9	13	10	—	—
Tail		—	—	—	30	31	—	—	—	—	—
Fuselage		45	39	—	42	36	—	2	17	—	—
Nacelle		9	9	22	4	—	20	8	20	—	—
ZMEW		0.8	0.7	0.5	0.6	0.5	0.2	0.1	0.2	0.1	0.1

* Includes 303 pounds of "D" ducts and leading edge inner skin transferred from the nacelle system weight, and 44 pounds of windshield wiper and rain repellent system transferred from the furnishings and equipment system.

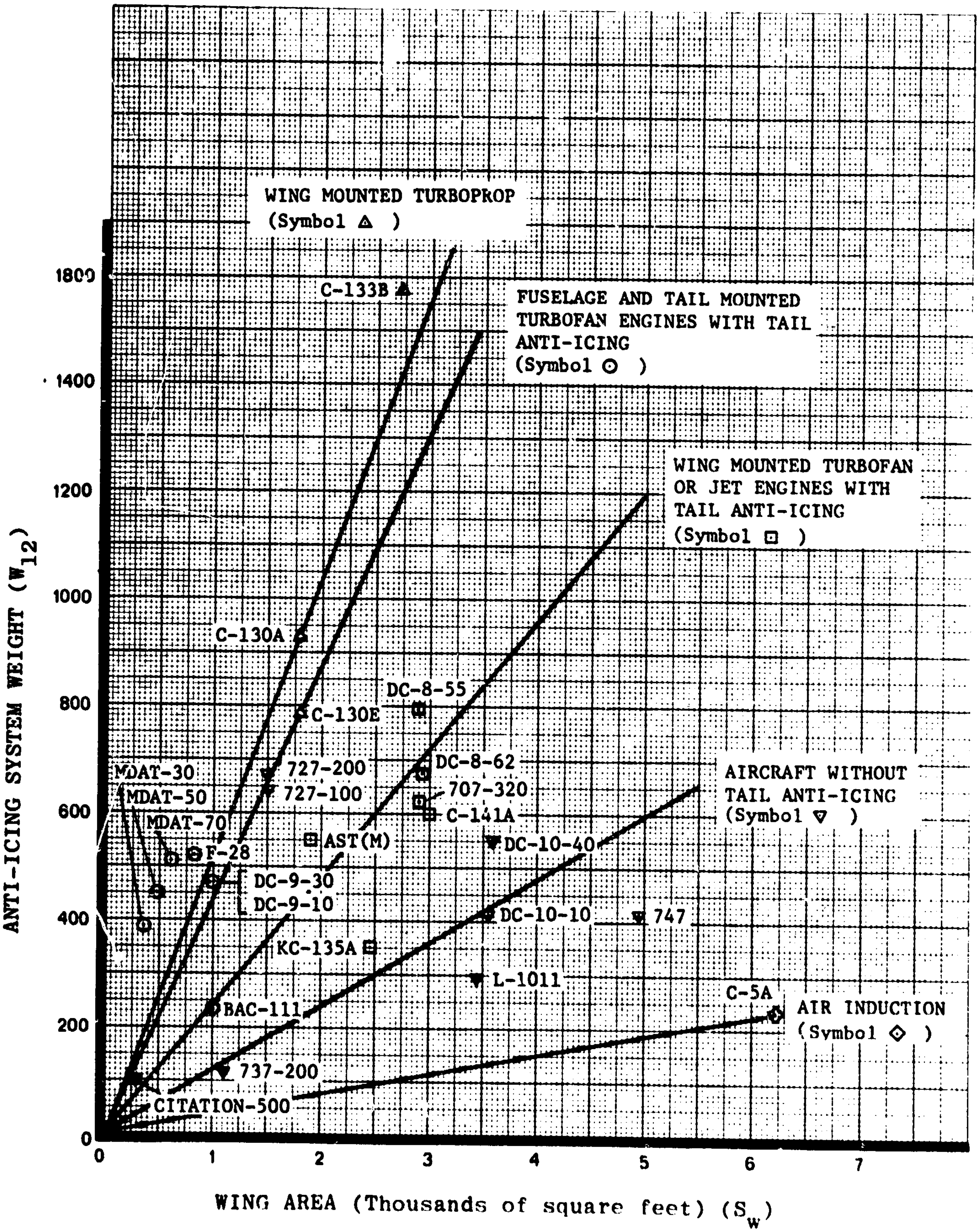
Table 5.23

ANTI-ICING SYSTEM WEIGHT DATA - MILITARY AIRCRAFT

	Symbol	C-130A	C-130E	KC-135A	C-133B	C-141A	C-5A	AST(M)
Anti-Icing	W_{12}	932	785	350	1,575	598	233	552
Ducting, Valves, Elect. Heaters, & Insulation		645	556	204	822	204	139	375
Wing		303	260	86	461	133	—	79
Tail		161	121	43	261	20	—	72
Air Induction		128	146	75	29	51	139	187
Miscellaneous		53	29	—	71	—	—	37
Controls, Wiring, Switches, Plumbing		191	163	129	693	367	81	142
Wing		24	31	—	186	20	—	13
Tail		11	3	20	70	118	—	14
Air Induction		—	6	—	106	33	45	—
Windshield		78	64	—	82	—	—	—
Rain Repellent/Windshield Wipers		55	54	109	206	196	36	58
Miscellaneous (Incl. Propeller)		23	5	—	43	—	—	57
Supports and Attach		96	66	17	60	27	13	35
Wing		24	21	8	33	23	—	10
Tail		34	21	1	6	3	—	25
Fuselage		7	7	—	8	—	2	—
Nacelle		31	17	8	13	1	11	—
%MEW		1.5	1.1	0.4	1.3	0.5	0.1	0.5

Figure 5.35

ANTI-ICING SYSTEM WER



Aircraft with fuselage and/or tail mounted engines usually have heavier anti-icing weights because separate hot air ducts must be routed from the aft fuselage engine location to the wing. The anti-icing weights for aircraft with turbo-prop engines reflect the additional components required for the propeller anti-icing systems.

Based on averages for the different configurations, anti-icing system WERs are:

$W_{12} = 0.038\ S_w$	Nacelle Air Induction and Misc. Only
$W_{12} = 0.120\ S_w$	Wing Mounted Turbofan or Jet Engines Without Tail Anti-icing
$W_{12} = 0.238\ S_w$	Wing Mounted Turbofan or Jet Engines with Tail Anti-icing
$W_{12} = 0.436\ S_w$	Fuselage and/or Tail Mounted Turbofan Engines with Tail Anti-icing
$W_{12} = 0.520\ S_w$	Wing Mounted Turboprop Engines with Tail Anti-icing

I. FURNISHINGS AND EQUIPMENT SYSTEM

Weight and Design Characteristics

Weight and design characteristics for the furnishings and equipment system are presented in Tables 5.24 and 5.25 for commercial and military aircraft, respectively.

Weight Estimating Relationships

The furnishings and equipment system weight was found to correlate well with the number of passengers for commercial transports and with the body wetted area for military transports. These data are plotted in Figures 5.36 and 5.37. Separate WERs were developed for medium and large transports and small transports. The difference between the two sizes occurs at about 80 passengers. The military transport furnishings and equipment weights shown in Figure 5.37 have been adjusted for comparability between aircraft by removing the weights of troop seats, cargo and aerial delivery systems, food, water, ditching and survival equipment, litters and supports, and the oxygen system. The military transport data in Table 5.25 were supplemented with data for small military transports in Figure 5.37. An extrapolation of the medium and large transport data would have indicated a very high weight for small transports, but the supplemental data provides a basis for a separate WER for small military transports.

The equations are:

$$W_{14} = 62.3\ N_p + 290 \qquad \text{Commercial } N_p \leq 80$$

$$W_{14} = 118.4\ N_p - 4{,}190 \qquad \text{Commercial } N_p > 80$$

$$W_{14} = 0.650\ S_b \qquad \text{Military } S_b \leq 4{,}500$$

$$W_{14} = 0.271\ S_b + 1{,}710 \qquad \text{Military } S_b > 4{,}500$$

Table 5.24

FURNISHINGS AND EQUIPMENT SYSTEM WEIGHT AND DESIGN DATA - COMMERCIAL AIRCRAFT

Weight Data	Symbol	Citation-500	MDAT-30	MDAT-50	F-28	MDAT-70	DC-9-10	BAC-111	DC-9-30	727-100
Furnishings and Equipment	W_{14}	794	2,657	3,548	3,535	4,772	6,800	7,771	8,544	11,962
Seats and Chairs		365	748	1,154	1,369	1,577	2,296	2,866	3,029	4,604
Pilot and Copilot		80	105	105	105	105	111	103	113	119
Flight Engineer		—	—	—	—	—	—	—	—	77
Observer and Navigator		—	18	18	19	18	19	42	19	33
Cabin Attendant Station		—	17	17	34	34	61	65	62	70
Passenger Seats		257	570	950	1,134	1,330	1,895	2,171	2,572	4,017
Passenger Seat Tracks and Track Cover		28	38	64	77	90	210	485	263	288
Passenger Accommodations and Furnishings		367	1,810	2,244	2,044	2,994	4,272	4,699	5,316	7,022
Lavatory Equipment and Installation		14	233	233	78	466	255	287	345	646
Fresh Water System		—	50	50	15	100	64	151	99	135
Paneling, Lining, and Trim		96	536	722	1,029	942	1,284	1,142	1,618	1,563
Utility Racks and Passenger Service Units		—	184	307	—	430	638	588	847	691
Cargo Handling System		5	5	8	—	11	45	27	48	244
Galley Equipment and Structure		29	180	180	101	180	480	320	576	983
Floor Covering		36	79	100	110	121	271	257	321	449
Thermal/Acoustic Material		95	287	364	304	440	690	1,064	774	1,475
Instrument Panels and Glare Shields		22	28	28	40	28	33	71	34	93
Consoles and Pedestals		10	55	55	146	55	67	56	67	94
Partitions and Doors		23	83	83	167	83	250	414	294	150
Utility Trays and Divider Tables		—	—	—	—	—	18	—	18	—
Coatroom, Cockpit and Crew Stowage		5	27	45	3	63	59	44	125	229
Oxygen System		32	63	89	51	75	118	273	150	270
Emergency Equipment		26	65	107	78	149	158	125	169	211
Exterior Finish		36	34	43	44	52	74	81	80	125
%MEW		12.4	13.0	13.3	10.6	14.0	14.2	15.0	15.5	14.4
Design Data										
No. of Passengers (Coach)/Abreast Seating	N_P	8/2	30/4	50/4	60/5	70/4	80/5	99/5	110/5	138/6
Seat Pitch/Seat Width (In)		—	34/20	34/20	33/21	34/20	34/21	34/—	34/21	34/20
No. of Cabin Attendants		—	1	1	2	2	2	3	3	3
No. of Lavatories		1	1	1	1	2	2	2	3	3
No. of Galleys		1	1	1	1	1	2	3	2	2
Cabin Length (In)		160	310	480	516	650	669	844	848	860
Cabin Floor Width (In)		38	91	91	113	91	116	114	116	130
Cargo Compartment Length (Constant Section) (In)		67	190	360	337	530	441	454	620	340
Cargo Compartment Floor Width (In)		38	59	59	63	59	68	36	68	70
Fuselage Periphery (In)		201	361	361	316	361	431	421	431	481

Table 5.24 (Continued)

FURNISHINGS AND EQUIPMENT SYSTEM WEIGHT AND DESIGN DATA - COMMERCIAL AIRCRAFT

Weight Data	Symbol	727-200	707-320	DC-8-55	DC-8-62	DC-10-10	L-1011	747-200-B*
Furnishings and Equipment	W_{14}	14,779	16,875	15,884	15,340	38,072	32,829	48,007
Seats and Chairs		4,385	6,429	6,183	5,310	14,195	12,757	16,350
Pilot and Copilot		121	120	112	111	150	135	97
Flight Engineer		77	53	73	65	78	62	70
Observer and Navigator		33	91	109	109	100	51	36
Cabin Attendant Station		84	107	63	62	431	296	483
Passenger Seats		3,765	6,058	5,322	4,477	12,453	10,558	14,184
Passenger Seat Tracks and Track Cover		304	—	504	486	983	1,655	1,480
Passenger Accommodations and Furnishings		10,029	9,938	9,196	9,546	23,039	19,325	29,906
Lavatory Equipment and Installation		645	1,282	533	528	1,550	591	3,067
Fresh Water System		138	170	172	171	294	567	386
Paneling, Lining, and Trim		2,337	2,931	2,599	2,851	4,627	3,885	5,796
Utility Racks and Passenger Service Units		1,238		1,125	1,384	1,603	1,773	3,059
Cargo Handling System		100	—	30	31	1,256	816	2,998
Galley Equipment and Structure		2,334	1,104	1,533	1,516	8,157	6,577	7,909
Floor Covering		596	589	540	678	1,002	963	1,396
Thermal/Acoustic Material		1,487	2,368	1,559	1,400	2,165	2,176	3,380
Instrument Panels and Glare Shields		106	90	96	122	190	193	105
Consoles and Pedestals		101	64	47	49	86	32	54
Partitions and Doors		386	348	613	498	497	681	603
Utility Trays and Divider Tables		—	8	37	20	147	—	—
Coatroom, Cockpit and Crew Stowage		254	344	73	67	927	568	691
Oxygen System		307	640	239	241	538	503	462
Emergency Equipment		260	403	415	414	633	557	1,004
Exterior Finish		105	105	90	70	205	190	747
%MEW		15.4	13.7	12.1	11.4	17.0	14.7	14.4
Design Data								
No. of Passengers (Coach)/Abreast Seating	N_P	158/6	162/6	165/6	189/6	330/9	330/9	435/10
Seat Pitch/Seat Width (In)		34/20	34/20	34/20	34/20	34/20	34/20	34/20
No. of Cabin Attendants		3	4	3	4	10	8	14
No. of Lavatories		3	5	4	5	7	7	12
No. of Galleys		2	4	4	6	—	—	7
Cabin Length (In)		1,112	1,103	1,248	1,328	1,607	1,612	2,225
Cabin Floor Width (In)		139	127	130	130	218	220	223
Cargo Compartment Length (Constant Section) (In)		580	426	530	610	492	515	1,010
Cargo Compartment Floor Width (In)		70	73	82	82	124	96	125
Fuselage Periphery (In)		481	500	484	484	745	738	825

* Detail control book furnishings weight has been modified to include 7,900 pounds of galley structure (transferred from the operator items weight), 3,780 pounds of additional seats (revised to all coach passenger seating--435--at 34 inch seat pitch), and 2,686 pounds of additional seat weight to make them comparable to the DC-10 type seat comfort level. Also, 2,558 pounds of furnishings weight has been transferred to the other groups. Net increase is 11,808 pounds.

Table 5.25

FURNISHINGS AND EQUIPMENT SYSTEM WEIGHT AND DESIGN DATA - MILITARY AIRCRAFT

	Symbol	C-130E	C-133B	C-141A	C-5A	AST(M)
Weight Data						
Furnishings and Equipment	W_{14}	4,770	4,549	4,362	7,811	6,870
Seats and Chairs		1,639	369	535	805	1,641
Pilot and Copilot		145	151	134	141	151
Flight Engr/Navigator		105	104	108	143	--
Load Master/Observer		—	92	59	80	29
Troop Seats and Tracks		1,046	22	145	441	830
Litters and Supports		343	—	89	—	631
Accommodations & Furnishings		2,716	3,314	3,398	5,367	4,463
Crew Bunks and Supports		132	306	97	138	—
Lavatory Installation		110	38	156	102	109
Fresh Water System		57	17	11	86	20
Galley Equip. & Lockers		259	212	224	700	128
Manuals & Data Cases		6	87	14	21	81
Cargo and Aerial Delivery*		455	708	588	679	1,326
Water and Food		—	—	—	—	230
Paratroop Equipment		—	—	51	—	149
Instr. Panel & Glare Shield		95	70	94	41	90
Consoles and Pedestals		25	140	99	64	84
Floor Covering		46	53	25	137	48
Thermal/Acoustic Material		756	424	787	1,065	} 1,537
Partitions and Doors		27	482	174	683	
Lining and Trim		107	389	626	1,259	—
Platform and Ground Equip.		329	—	16	64	177
Misc. Equipment		89	175	33	28	109
Oxygen System		223	213	403	300	375
Emergency Equipment		415	866	395	430	696
Exterior Finish		—	—	34	1,209	70
[illegible]		6.9	3.8	3.4	2.4	6.1
Design Data						
Fuselage Wetted Area (Ft^2)	S_b	3,339	6,900	5,096	16,507	4,563
No. of Bunks/Litters		--/8	4/0	2/0	6/0	0/6
No. of Troop Seats		60	0	0	15	74
Cargo Floor Length (In.)		492	982	840	1,453	560
Cargo Floor Width (In.)		118	143	117	228	140
Ramp Length (Loadable) (In.)		132	186	106	283	150
Fuselage Periphery (In.)		517	617	534	892	679

*Weight includes winch, winch power drive, tie-down fittings and chains, tie-down stowage, and motorized pry bar. Rails, latches, rollers, powered rollers and sub-systems, and auxiliary ramp powered conveyor systems are located in the fuselage weight.

Figure 5.36

FURNISHINGS AND EQUIPMENT SYSTEM WER - COMMERCIAL AIRCRAFT

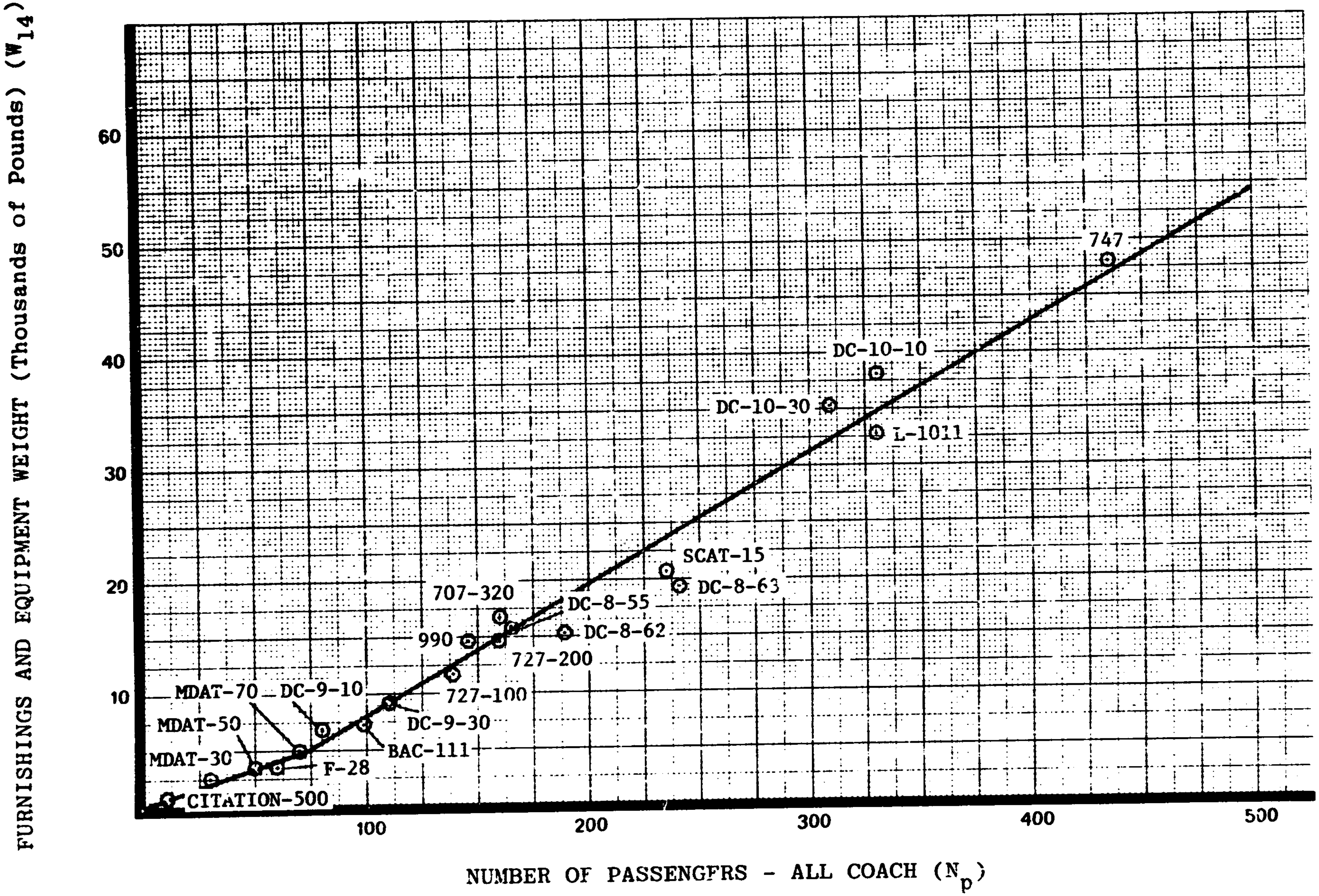
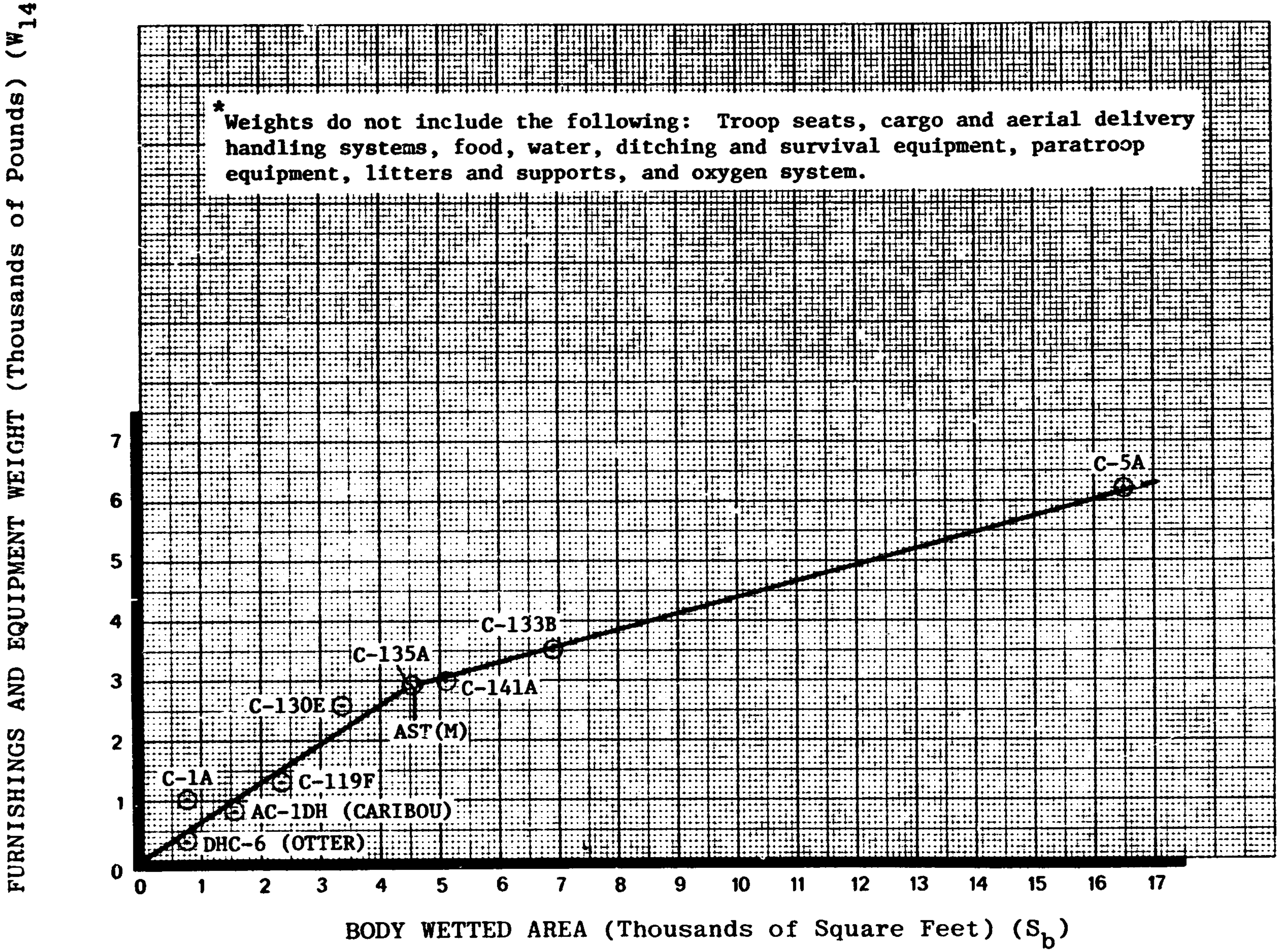


Figure 5.37

FURNISHINGS AND EQUIPMENT WER - MILITARY AIRCRAFT*



J. INSTRUMENTS SYSTEM

Weight Characteristics

Weight breakdowns for the instruments system are presented in Tables 5.26 and 5.27 for commercial and military aircraft, respectively.

Weight Estimating Relationships

The instruments system weight is very hard to correlate since the number and types of components depend on many things such as number of engines, length of wire run from the signal input point to the cockpit, degree of sophistication and redundancy, and the type of visual display. To obtain the best results, fuel quantity related, propulsion related, and all other instruments were correlated separately. The weights of the instruments in each category were correlated with several independent variables. For example, fuel quantity instruments were correlated with fuel volume (data from Table 5.9), the number of fuel tanks, and wing span times the number of fuel tanks. The best correlation for fuel instruments weight was with fuel volume; this is plotted in Figure 5.39. The best correlation for propulsion instruments (engine and fuel flow instruments) weight was with engine thrust (data from Table 5.9). Propulsion instrument weights per engine are plotted in Figure 5.39. The weight of the other instruments was best correlated with the number of passengers (data from Table 5.1) for commercial transports and with the body wetted area (data from Table 5.2) for military transports. The other instruments weights are plotted in Figure 5.40. Data for commercial and military transports were included in the same correlations. Therefore, for "other" instruments a dual scale was used based on an approximate relationship between number of passengers and body wetted area.

Weights for the C-5A, MDAT-30 and MDAT-70 were not included in the correlations because the C-5A used extraordinary weight saving techniques and, because of study ground rules, MDAT-30 and MDAT-70 instrument weights were not modified in accordance with geometry changes.

Although there is considerable scatter indicated in the plots in Figures 5.38, 5.39 and 5.40, approximate WERs were derived as follows:

Table 5.26

INSTRUMENT SYSTEM WEIGHT DATA - COMMERCIAL AIRCRAFT

	Symbol	Citation-500	MDAT-30	MDAT-50	F-28	MDAT-70	DC-9-10	BAC-111	DC-9-30	737-200
Instrument System Weight	W_{15}	76	300	300	275	300	490	504	575	518
Flight		35	37	37	55	37	105	199	108	182
Control Surface		—	5	5	20	5	8	19	12	41
Electrical		2	4	4	8	4	6	2	6	—
Hydraulic		—	9	9	20	9	15	17	15	16
Pneumatic		—	5	5	9	5	9	9	9	—
Propulsion		22	79	79	83	79	126	78	132	103
Fuel Quantity		6	44	44	32	44	73	43	84	79
Warning		11	117	117	48	117	148	137	209	97
%MEW		1.2	1.5	1.1	0.8	0.9	1.0	1.0	1.0	0.9

Table 5.26 (Continued)

INSTRUMENT SYSTEM WEIGHT DATA - COMMERCIAL AIRCRAFT

	Symbol	727-100	727-200	707-320	DC-8-55	DC-8-62	DC-10-10	L-1011	DC-10-40	747	SCAT-15
Instrument System Weight	W_{15}	723	827	550	1,002	916	1,349	1,016	1,645	1,486	3,400*
Flight		224	298	222	105	102	144	156	205	301	351
Control Surface		61	57	--	21	19	110	155	125	45	36
Electrical		--	--	--	10	8	15	--	16	32	8
Hydraulic		26	31	--	17	17	23	46	25	51	36
Pneumatic		19	23	--	14	12	29	45	29	11	--
Propulsion		158	165	121	255	229	213	294	343	300	213
Fuel Quantity		50	62	110	346	301	368	107	427	266	217
Warning		185	191	97	234	228	447	213	475	480	311
[illegible]		0.9	0.9	0.4	0.8	0.7	0.6	0.4	0.7	0.4	0.1

* Includes 2,228 pounds of miscellaneous wire and installation material.

Table 5.27

INSTRUMENT SYSTEM WEIGHT DATA - MILITARY AIRCRAFT

	Symbol	C-130A	KC-135A	C-133B	C-141A	C-5A	AST(M)
Instrument System Weight	W_I	559	382	563	899	734	994
Flight		89	112	96	229	232	219
Control Surface		7	17	7	24	17	38
Electrical		7	1	4	5	8	12
Hydraulic		10	26	8	14	12	19
Pneumatic		2	—	8	10	1	5
Propulsion		149	99	219	320	149	208
Fuel Quantity		104	71	148	165	136	209
Warning		44	8	59	93	42	284
Misc. Wire & Instal.		147	48	14	39	137	—
%MEW		0.9	0.4	0.5	0.7	0.2	0.9

Figure 5.38

FUEL QUANTITY INSTRUMENTS WER

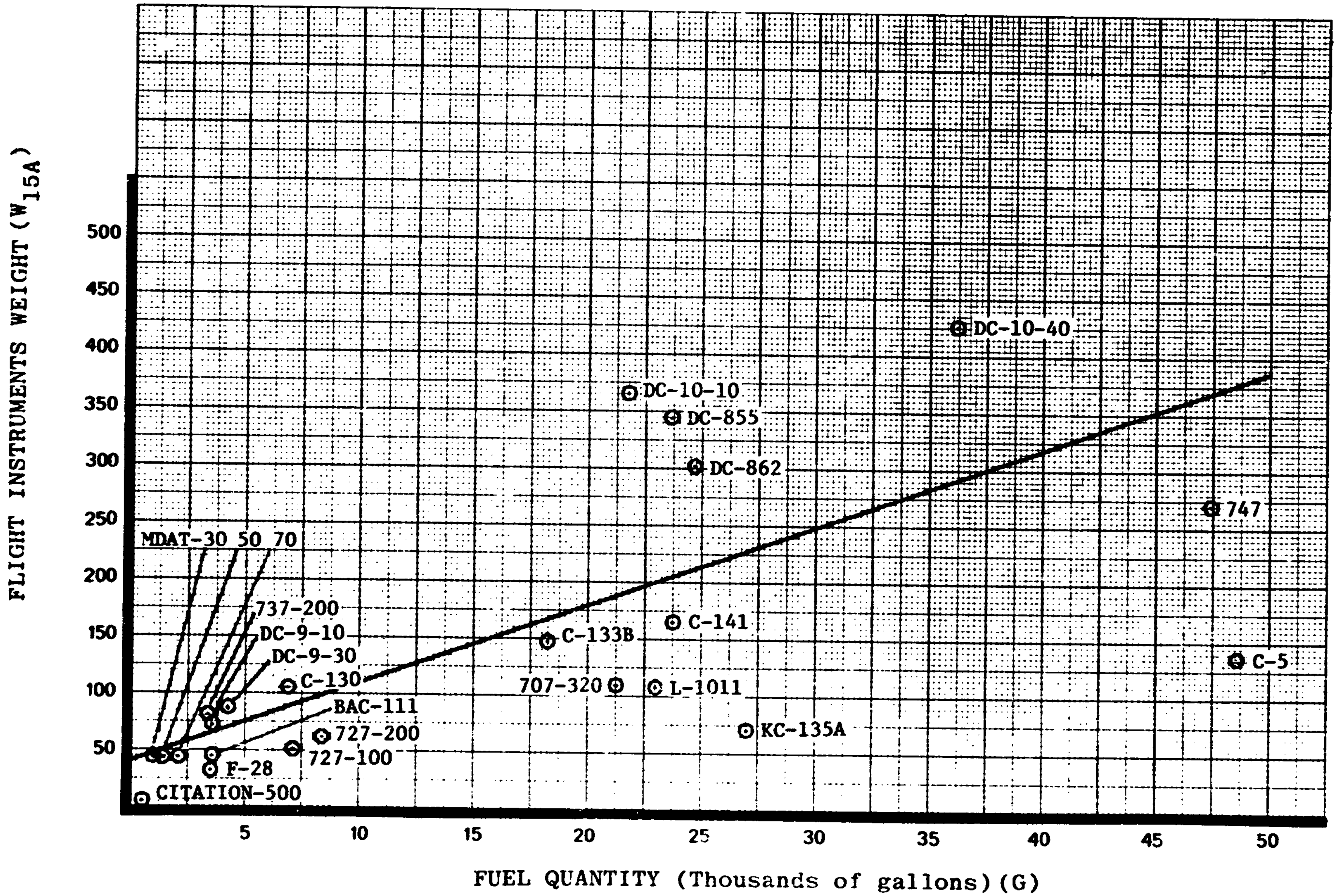


Table 5.39

PROPULSION INSTRUMENTS WER

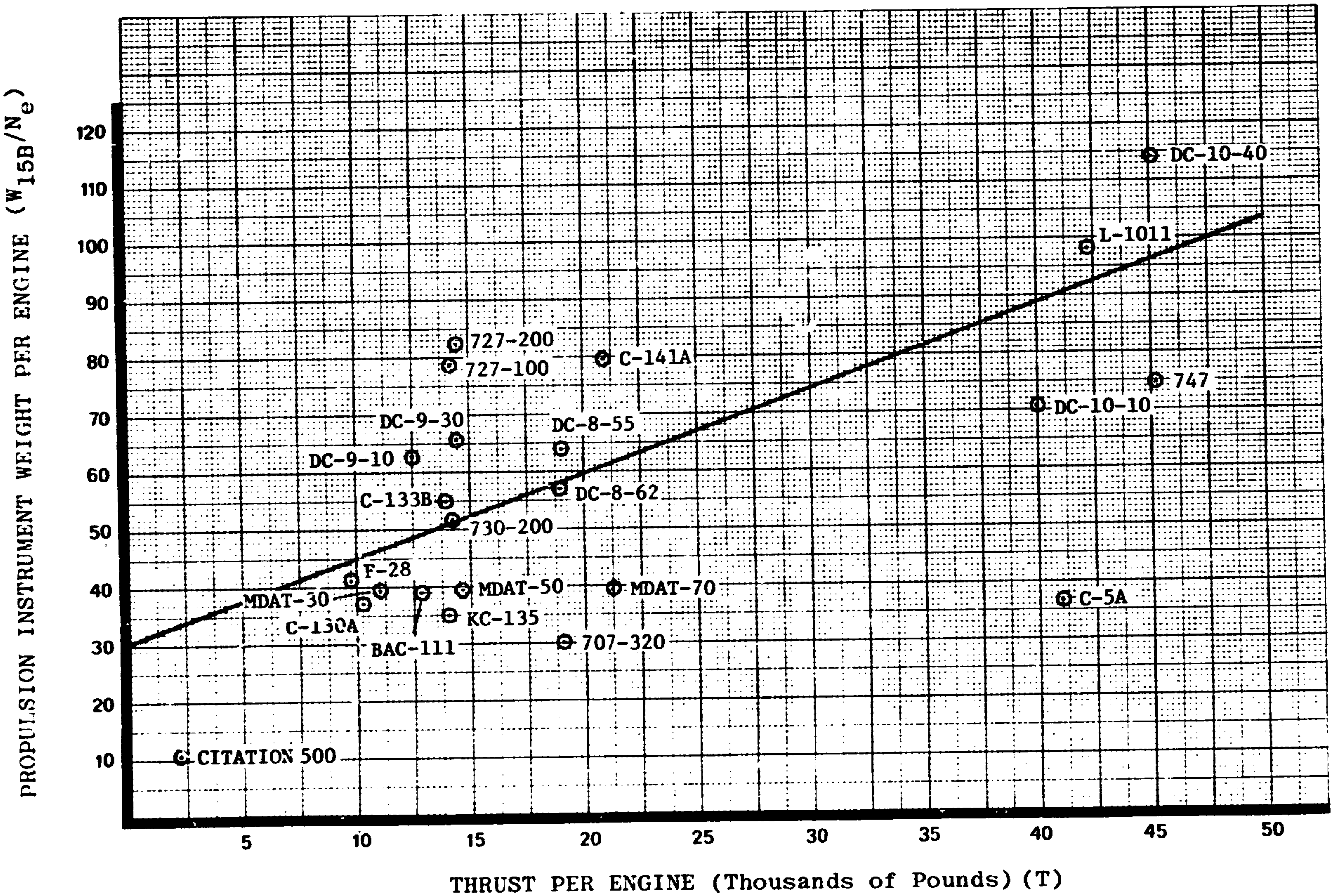
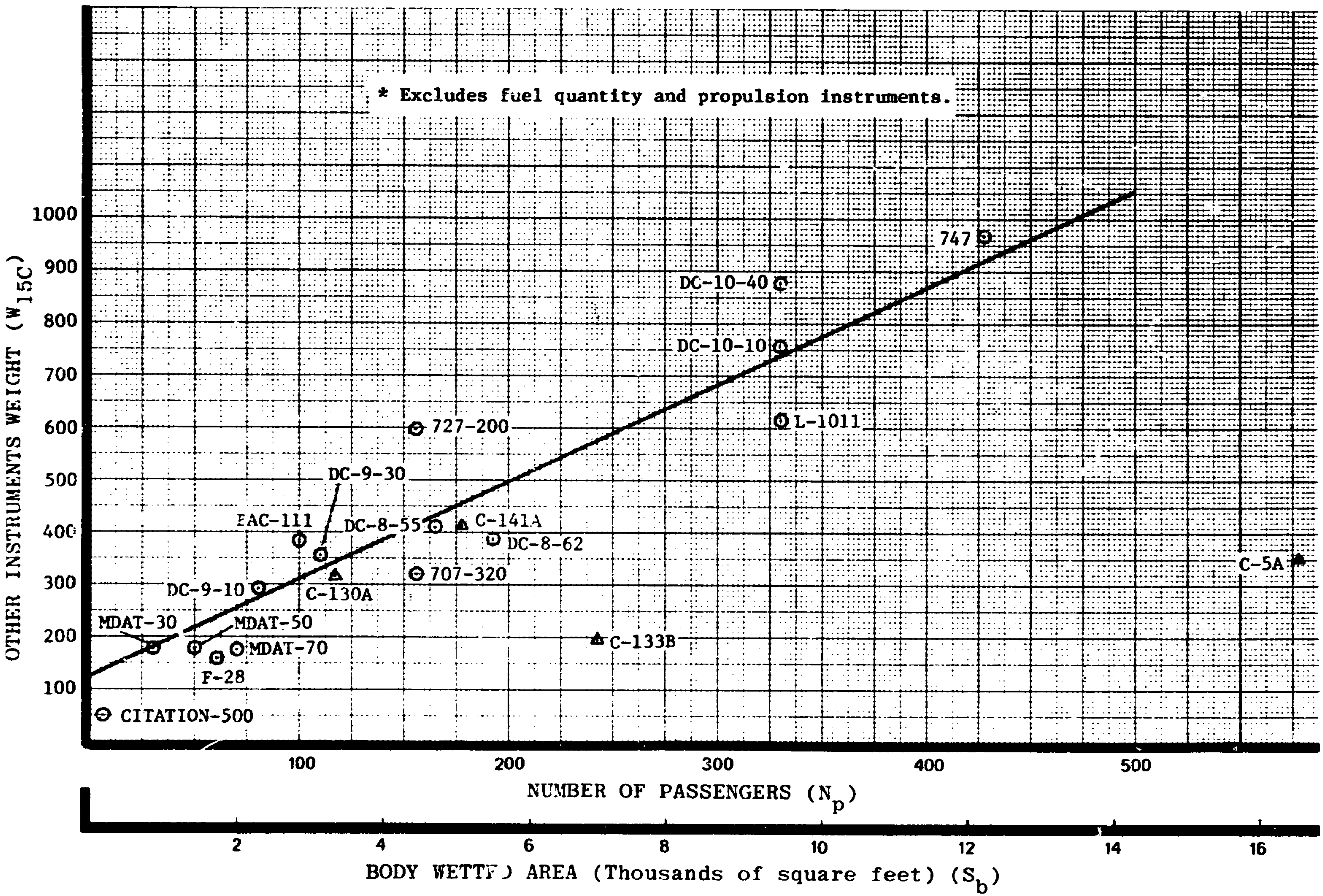


Figure 5.40

OTHER INSTRUMENTS* WER



W_{15A}	=	$0.00714\ G + 34$	Fuel Quantity Instruments
W_{15B}	=	$(0.00145\ T + 30)\ N_e$	Propulsion Instruments
W_{15C}	=	$1.872\ N_p + 128$	Other Instruments Commercial
W_{15C}	=	$0.0540\ S_b + 126$	Other Instruments Military

These equations can be combined as follows:

$$W_{15} = 1.872\ N_p + 0.00714\ G + (0.00145\ T + 30)\ N_e + 162 \quad \text{Commercial}$$

$$W_{15} = 0.0540\ S_b + 0.00714\ G + (0.00145\ T + 30)\ N_e + 160 \quad \text{Military}$$

As mentioned in Section 4, instruments are composed of two general categories of items - equipment (e.g., "blackboxes") and other items such as installation hardware and wiring. Each category accounts for about half of the total instrument system weight.

K. AVIONICS SYSTEM

Weight and Design Characteristics

The avionics weight and design characteristics are presented in Tables 5.28 and 5.29 for commercial and military aircraft, respectively. The design characteristics are given to aid in interpreting the weight data. Major weight differences are associated with customer requirements, certification goals, and type of equipment (e.g., vacuum tube vs. solid state). Minor weight differences are associated with equipment locations and fuselage size. Conventional versus automatic landing introduces a negligible weight penalty to the avionics system, but the latter must have anti-throttle, which is included with the propulsion controls.

Weight Estimating Relationships

Avionics systems were classified into six categories for weight correlation purposes as follows:

1. General Aviation
2. Category I or II Domestic
3. Category I or II Overwater
4. Category III Domestic
5. Category III Overwater
6. Military

These avionics categories account for the major differences in avionics weight among transport aircraft. For a given category, aircraft size will also have some effect on the avionics weight.

WERs were developed for the first five avionics categories, all of which are related to commercial transports, using the following method. First, the average weight and average number of passengers were determined for each category.* Then, the effect of aircraft size on avionics weight was

* The MDAT-30, 747 and SCAT-15 avionics weights were not used in computing the averages. The MDAT-30 was sized from the MDAT-50 and assumed to have an identical avionics weight. The 747 avionics weight includes a large compliment of movie projection equipment. The SCAT-15 is a special case.

Table 5.28

AVIONICS SYSTEM WEIGHT AND DESIGN DATA - COMMERCIAL AIRCRAFT

	Symbol	Citation 500	MDAT-30	MDAT-50	F-28	MDAT-70	DC-9-10	BAC-111	DC-9-30	737-200	727-100
Avionics Weight Data	W_{16}	321	586	586	923	586	1,039	1,368	1,108	1,100	1,844
Integrated Flight Guidance and Controls		119	150	150	270	150	349	506	375	311	463
Units		82	89	89	183	89	236	262	243	—	190
Servo Mechanism		17	20	20	—	20	18	64	20	—	22
Installation		20	41	41	87	41	95	179	112	—	251
Communications		32	137	137	141	137	198	171	230	298	433
Internal		5	91	91	82	91	116	93	146	118	277
Units		—	38	38	43	38	71	59	74	—	—
Tape Reproducer		—	—	—	—	—	—	—	—	—	—
Installation		—	53	53	39	53	45	34	72	—	—
External		27	46	46	59	46	82	78	84	180	156
Units		21	12	12	44	12	43	34	43	—	—
Antenna		3	4	4	—	4	4	6	4	—	—
Installation		3	30	30	15	30	35	38	37	—	—
Navigation		160	229	229	347	229	383	401	394	244	506
Units		119	104	104	246	104	134	226	149	—	—
Antenna		16	13	13	—	13	45	35	58	—	—
Installation		25	112	112	101	112	204	140	187	—	—
Miscellaneous Equipment		10	70	70	165	70	109	290	109	247	442
Flight Recorder		—	—	—	25	—	6	46	5	38	64
Voice Recorder		—	—	—	37	—	—	—	—	36	—
AIDS		—	—	—	—	—	—	—	—	—	—
Equipment Rack Structure		6	70	70	56	70	99	172	100	129	244
Misc. Units		—	—	—	—	—	—	21	—	—	—
Misc. Installation		4	—	—	47	—	4	51	4	44	134
Summary		244	237	237	563	237	477	681	591	—	—
Units		52	236	236	289	236	383	442	412	—	—
Installation		6	70	70	56	70	99	172	100	129	244
Rack Structure		19	43	43	15	43	80	73	95	—	—
Antenna		0.76	0.40	0.40	0.61	0.40	0.46	0.50	0.53	—	—
Ratio of Units to Total		5.0	2.9	2.2	2.8	1.7	2.2	2.6	2.0	2.0	2.2
TMEW											
Design Data		II	II	II	II	II	I	I	II	II	II
Category		Domestic	Domestic	Domestic	Domestic	Domestic	Domestic	Domestic	Domestic	Domestic	Domestic
Operation		Manual	Manual	Manual	Manual	Manual	Manual	Manual	Manual	Manual	Manual
Landing		1,350	850	850	400	850	840	860	900	900	1,800
Design Range (N-Mile @ Max Payload)		491	636	806	966	976	1,105	1,168	1,284	1,163	1,394
Fuselage Length (In.)	L_b										

Table 5.28 (Continued)

AVIONICS SYSTEM WEIGHT AND DESIGN DATA - COMMERCIAL AIRCRAFT

	Symbol	727-200	707-320B	DC-8-55	DC-10-10	L-1011	DC-10-40	747	SCAT-15
Avionics Weight Data	W_{16}	1,819	1,815	1,870	2,827	2,967	3,186	4,134	4,178
Integrated Flight Guidance and Controls		478	231	437	998	1,047	1,150	824	1,951
Units		233	—	243	586	397	700	386	1,026
Servo Mechanism		22	—	30	—	53	—	—	—
Installation		223	—	164	412	597	450	438	925
Communications		350	600	621	685	887	929	1,916	618
Internal		239	148	171	588	760	528	1,571	254
Units		64	76	74	201	263	195	1,363	135
Tape Reproducer		27	—	—	16	23	19	20	—
Installation		148	72	97	371	474	314	188	119
External		111	452	450	97	127	401	345	364
Units		61	226	279	43	45	244	159	206
Antenna		16	84	6	7	11	33	28	116
Installation		34	142	165	47	71	124	158	42
Navigation		538	584	555	804	582	772	746	484
Units		256	297	268	390	286	382	304	322
Antenna		138	45	53	287	64	232	122	92
Installation		144	242	234	127	232	158	320	70
Miscellaneous Equipment		453	400	257	340	451	335	648	1,125
Flight Recorder		56	—	47	53	47	62	97	38
Voice Recorder		62	—	—	41	43	39	39	20
AIDS		—	—	—	46	—	10	—	—
Equipment Rack Structure		281	213	120	200	217	216	245	390
Misc. Units		—	—	—	—	67	—	—	—
Misc. Installation		54	187	90	—	77	8	267	677
Summary									
Units		786	—	941	1,330	1,224	1,641	2,368	1,747
Installation		603	—	750	1,003	1,451	1,064	1,371	1,833
Rack Structure		281	213	120	200	217	216	245	390
Antenna		149	—	59	294	75	265	150	208
Ratio of Units to Total		0.43	—	0.50	0.47	0.41	0.52	0.57	0.42
%MEW		1.9	1.5	1.4	1.3	1.3	1.3	1.2	1.4
Design Data									
Category		II	II	II	III	III	III	II	III
Operation		Domestic	Overwater	Overwater	Domestic	Domestic	Overwater	Overwater	Overwater
Landing		Manual	Manual	Manual	Automatic	Autiomatic	Automatic	Automatic	Automatic
Design Range (N-Mile @ Max Payload)		--	4,600	4,100	2,300	1,900	3,300	5,250	3,600
Fuselage Length (In.)	L_b	1,634	1,746	1,755	2,046	2,132	2,046	2,702	3,540

Table 5.29

AVIONICS SYSTEM WEIGHT AND DESIGN DATA - MILITARY AIRCRAFT

	Symbol	C-130E	C-133B	C-141A	C-5A	AST(M)
Avionics Weight Data	W_{16}	2,657	2,630	2,938	4,130	2,919
Integrated Flight Guidance and Controls		423	557	473	835	543
Units		236	209	205	498	296
Servo Mechanism		53	74	34	23	66
Installation		134	274	234	314	181
Communications		516	609	729	731	322
Internal		153	132	192	192	71
Units		81	45	80	95	47
Installation		72	87	112	97	24
External		363	477	537	539	251
Units		274	292	335	326	88
Antennas		21	13	55	18	19
Installation		68	172	147	195	144
Navigation		1,440	1,265	1,378	1,416	1,711
Units		691	569	711	821	1,095
Antennas		169	126	113	94	214
Installation		580	571	554	501	402
Miscellaneous Equipment		278	198	358	1,148	343
Flight/Voice Recorder		—	—	29	151	134
Radar		—	—	—	—	—
Units		—	—	—	388	—
Installation		—	—	—	251	—
Equipment Rack Structure		278	173	172	201	135
Misc. Installation		—	25	157	54	6
Weight and Balance		—	—	—	—	—
Units		—	—	—	49	37
Installation		—	—	—	54	31
Summary						
Units		1,335	1,189	1,394	2,351	1,763
Installation		854	1,129	1,204	1,466	788
Equipment Rack Structure		278	173	172	201	135
Antenna		190	139	168	112	233
Ratio of Units to Total		0.50	0.45	0.47	0.57	0.60
%MEW		3.8	2.2	2.3	1.3	2.6
Design Data						
Operation		Overwater	Overwater	Overwater	Overwater	Overwater
Fuselage Length (In.)		1,172	1,839	1,587	2,767	1,207

determined. For passenger aircraft, the avionics subsystem affected most by aircraft size is the internal communications subsystem which includes the public address and entertainment systems. The average pounds per passenger for internal communications is 1.5 pounds per passenger. In order to determine the effect of aircraft size on the remainder of the avionics weight, a comparison was made between the DC-9-10 and DC-9-30 as equipped for the same customer. The difference in avionics weight (less internal communications) between these two aircraft is 39 pounds. Since the DC-9-30 carries 30 more passengers, the added avionics weight (less internal communications) is 1.3 pounds per passenger. Therefore, for passenger aircraft, there is a total avionics weight variation of approximately 2.8 pounds per passenger. Finally, for each category, an equation is derived which has the following form:

$$W_{16} = 2.8\ N_p + C$$

"C" is a constant which is determined from the average weight and average number of passengers for each category. The weight data and WERs are plotted in Figure 5.40. The commercial aircraft avionics WER's are:

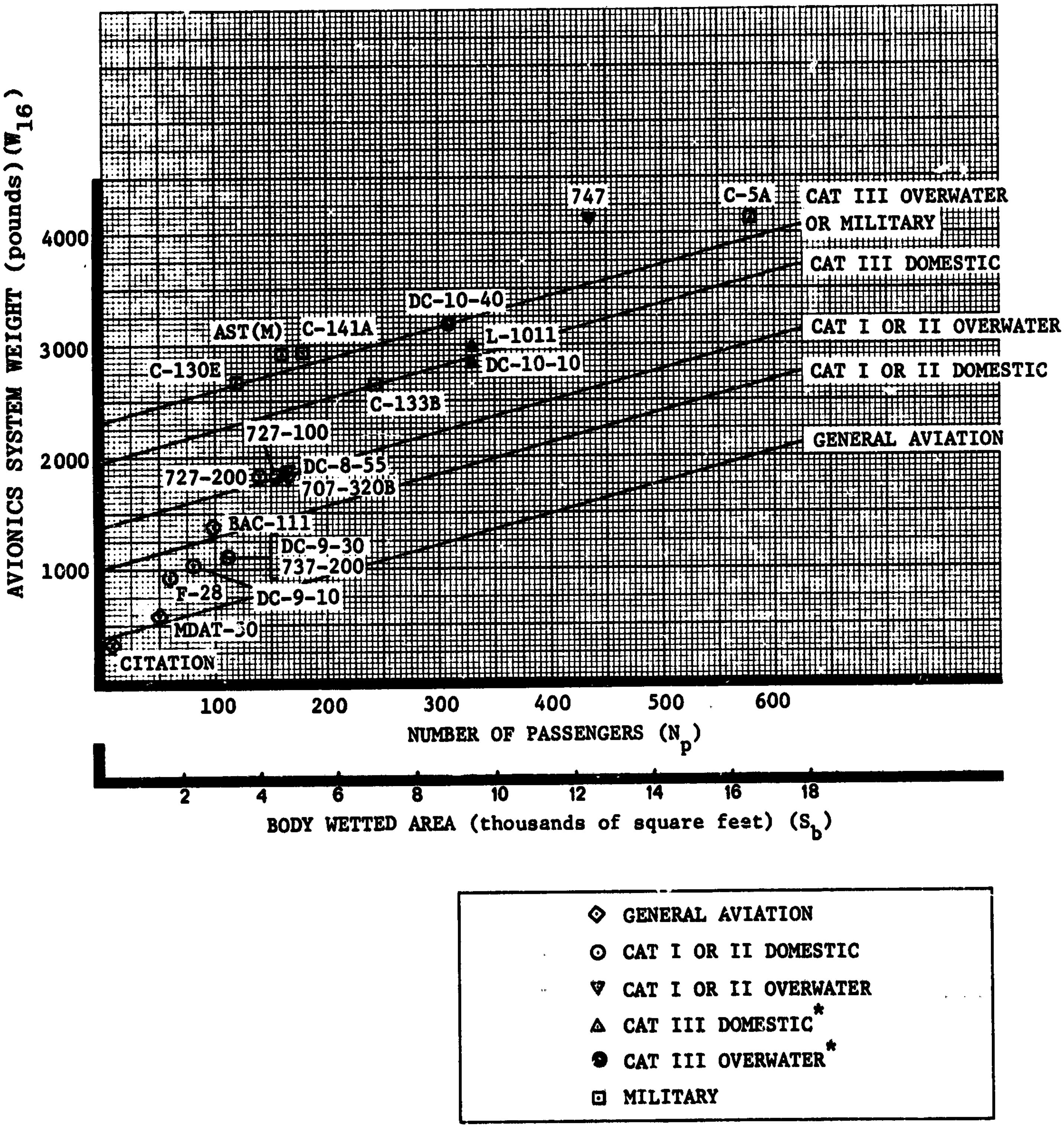
$W_{16} = 2.8\ N_p + 370$	General Aviation
$W_{16} = 2.8\ N_p + 1{,}010$	Category I or II Domestic
$W_{16} = 2.8\ N_p + 1{,}380$	Category I or II Overwater
$W_{16} = 2.8\ N_p + 1{,}970$	Category III Domestic
$W_{16} = 2.8\ N_p + 2{,}320$	Category III Overwater

The weight difference indicated by the equations for category I or II versus category III avionics is about 950 pounds. Studies indicate the actual difference for converting from category II to category III is approximately 300 pounds. The additional 650 pounds is characteristic of wide-body aircraft which include passenger entertainment, increased flight guidance reliability and maintainability, and performance monitoring.

The military WER is derived by correlating the military avionics weight with body wetted area. The result is very close to the category III overwater

Figure 5.41

AVIONICS SYSTEM WERs



* In addition to Category III avionics, these aircraft include approximately 650 pounds for passenger entertainment, increased flight guidance reliability and maintainability, and performance monitoring.

WER for passenger aircraft, given the typical relationship of body wetted area to number of passengers. The military weight data and WER are plotted in Figure 5.40. The WER is:

$$W_{16} = 0.10\, S_b + 2{,}330 \qquad \text{Military}$$

As mentioned in Section 4, avionics are composed of two general categories of items - equipment (e.g., "blackboxes" or units) and other items such as installation hardware, wiring and antennas. Each category accounts for about half of the total avionics system weight as shown by the "Ratio of Units to Total" in Tables 5.28 and 5.29.

L. LOAD AND HANDLING SYSTEM

Weight Characteristics and Analysis

The weights for the load and handling system are shown in Tables 5.30 and 5.31 for commercial and military transports, respectively.

Weight Estimating Relationships

Since the weight of the load and handling system has a negligible effect on the overall aircraft weight, average load and handling system weights for commercial and military transports are recommended for use in preliminary design studies.

The weights are:

$W_{17} = 50$ Commercial

$W_{17} = 130$ Military

Table 5.30

LOAD AND HANDLING SYSTEM WEIGHT DATA - COMMERCIAL AIRCRAFT

	Symbol	Citation-500	MDAT-30	MDAT-50	F-28	MDAT-70	DC-9-10	BAC-111	DC-9-30	737-200
Load and Handling	W_{17}	.2	20	20	—	20	19	9	57	10
Handling and Jacking Fittings		2	20	20	—	20	15	9	26	10
Miscellaneous		—	—	—	—	—	4	—	31	—
ΣMEW		—	0.1	0.1	—	0.1	—	—	0.1	—

Table 5.30 (Continued)

LOAD AND HANDLING SYSTEM WEIGHT DATA - COMMERCIAL AIRCRAFT

	Symbol	727-100	727-200	707-320	DC-8-55	DC-8-62	DC-10-10	L-1011	DC-10-40	747	SCAT-15
Load and Handling	W_{17}	15	19	—	55	54	62	—	62	228	—
Handling and Jacking Fittings		15	19	—	55	54	62	—	62	228	—
Miscellaneous		—	—	—	—	—	—	—	—	—	—
%MEW		—	—	—	—	—	—	—	—	0.1	—

Table 5.31

LOAD AND HANDLING SYSTEM WEIGHT DATA - MILITARY AIRCRAFT

	Symbol	C-130A	C-130E	KC-135A	C-133B	C-141A	C-5A	AST(M)
Load and Handling		61	61	--	105	104	273	150
Stabilizer Jacks		--	--	--	--	70	260	122
Handling and Jacking Fittings		7	7	--	105	34	13	28
Miscellaneous		54	54	--	--	--	--	--
%MEW		0.1	0.1	--	0.1	0.1	0.1	0.1

APPENDIX A

ESTIMATING ACTUAL COSTS FOR COMMERCIAL AIRCRAFT

The actual cost of a commercial transport aircraft is known only to the aircraft manufacturer that builds it. However, in order to check the reliability of the CERs developed in this paper as applied to commercial aircraft, it is necessary to estimate the actual cost, even if only approximately. A methodology for estimating the actual cost based on published price data is described below.

The price of a commercial aircraft tends to be constant (excluding inflation) for all units produced.[(13)*] Therefore, a buyer can typically purchase either the 10th unit or the 150th unit for the same price although the 10th would cost the manufacturer considerably more because of learning curve effects and the fact that non-recurring (e.g. design, test and tooling) costs are amortized over a much smaller quantity. Thus, the manufacturer incurs a defecit for the first "n" units sold and thereafter makes a profit.

If the manufacturer's non-recurring costs and breakeven point ("n") were known, then the actual cumulative average cost of "n" units could be determined. By using an approximate range of values for the non-recurring costs and breakeven point, the actual cost for "n" units can be approximated. Then, by using an 86 percent learning curve slope, which is typical

* The actual selling price may vary depending upon negotiations at the time of the sale that take into consideration items such as the quantity of aircraft and spare parts ordered and the prepayment schedule which, in essence, provides the aircraft manufacturer with an interest free loan by requiring the purchaser to pay as much as one third of the purchase price as early as nine months before delivery. The foregone interest on this amount represents a substantial cost to the purchaser (2 to 3 percent of the sales price) that is not reflected in the sales price of an aircraft.

for the aircraft industry, the cost for a quantity different from "n" (e.g., CAC_{100}) can be determined.

This methodology has been applied to the DC-10-10 as follows. The reported selling price (less engines) is \$18.2 million in 1975 dollars.[13] This amount includes items unrelated to the cost of producing an aircraft such as warranties, check out flight and state and local taxes. These items amount to about 4 percent of the reported sales price and when subtracted from the sales price result in an adjusted sales price of \$17.5 million. Assuming that non-recurring costs are between \$800 and \$1,200 million and that the breakeven is between 300 and 400, the CAC_{100} is estimated as follows:*

	Non-recurring Costs	
Breakeven	\$800M	\$1,200M
300 units	\$18.8M	\$17.2M
500 units	\$21.0M	\$19.6M

The average CAC_{100} is \$19.2 million which is about 5.5 percent higher than the sales price. The estimated actual cost must be multiplied by a factor of 1.1 (which represents a nominal 10 percent profit as discussed in Section 2) to achieve comparability with the CERs summarized on Table 2.1. The resulting estimated actual price is \$21.1 million for the DC-10-10 as indicated on Table 2.3. Similarly, the estimated actual cost of \$3.9 million for the F-28 in Table 2.5 is 16 percent (1.055 X 1.1) greater than the reported selling price of \$3.4 million.

* For example, \$17.5 million X 300 = \$800 million + CAC_{300} X 300. Therefore, CAC_{300} = \$14.8 million and CAC_{100} = \$18.8 million.

APPENDIX B

DESCRIPTIONS OF RECURRING COST ELEMENTS USED BY AIRCRAFT MANUFACTURERS*

IN-HOUSE PRODUCTION includes all labor and raw material related to the production of major components and subassemblies by the aircraft manufacturer. It includes the following cost elements which are described below: Fabrication, Sustaining Engineering and Sustaining Tooling Labor; and Raw Material.

Fabrication labor performs operations in the manufacturing of detailed parts from raw material which includes cutting, molding, forming, stamping, stretching, machining, heat treating, anodizing, plating, etching, and deburring. It also includes shop coordination, and material expediting.

Sustaining Engineering labor includes technical staff support, customer engineering and product development engineering labor.

Sustaining Tooling labor is expended for the modification and repair of jigs, dies, fixtures, molds, patterns, and other manufacturing aids.

Raw Material includes all raw material such as sheets, bars, and tubes as well as castings, forgings, and extrusions.

SUBCONTRACTOR includes all major components and subassemblies that are not produced by the aircraft manufacturer. Two cost elements are included: Outside Production and Purchased Equipment.

Outside Production typically includes major subcontracted items such as the power pack (nacelle and thrust reverser), landing gear (nose and main gears, wheels, brakes and tires) and body and wing sections.

* The terminology and grouping of elements vary for different manufacturers.

Purchased Equipment typically includes flight controls (control columns, rudder pedals, electrical controls and hydraulic and mechanical and actuators); hydraulics (pumps, manifolds, reservoirs, filters, plumbing, valves, instruments); electrical (generators, battery, wire, lights, power conversion equipment, power distribution and control equipment, and lighting); pneumatics (valves, ducts, manifolds); air conditioning (environmental control systems, instrumentation, valves, controls); anti-icing (ducts, electrical); auxiliary power unit; furnishings and equipment (seats, galleys and lavatories); instruments (flight and navigation systems) and avionics (communication, flight and navigation).

IN-HOUSE ASSEMBLY includes all labor provided by the aircraft manufacturer that is required in order to integrate major components and subassemblies into a finished aircraft. The following cost elements are included: Quality Control, Minor Assembly and Major Assembly.

Quality Control labor is concerned primarily with inspection of production and tooling hardware, and preparation and verification of tests and associated paperwork. Inspection of subcontractor supplied items, both in plant and out of plant, are considered to be overhead costs.

Minor Assembly labor includes those operations that contribute to the manufacturing of an end item consisting of two or more fabricated parts and/or the joining of two or more assembled parts into a major component. This may be accomplished by welding, riveting, soldering, bolting, bonding or other fastening methods.

Major Assembly labor is broken into three subcategories:

1. Sectional Assembly labor includes the effort that produces assemblies which are manufactured and controlled to a unique configuration of a specific airplane. It includes both "non-position" and "fixed position" stages of the airframe construction. The "non-position" operations can be set up

in any factory location where space is available and usually result in subassemblies that will be used in the "fixed positions." The "fixed positions" in the factory area can result in a completed structural subsection or a whole section.

2. Installation and Checkout labor operations are performed in installing non-structural equipment and systems in an air vehicle or a section of an air vehicle. Operational and air-worthiness checks of both equipment and airframe structure are also included as is the installation and checkout of all electronics, avionics, electrical systems and wiring.

3. Miscellaneous labor consists of operations such as metal bond testing, cleaning, sealing, and painting.

APPENDIX C

SUMMARY OF SYSTEMS DESCRIPTIONS

A. WING, TAIL AND BODY SYSTEMS

The wing, tail and body structural systems are considered together for they have similar designs and use similar materials and methods of fabrication.

The wing system consists of the wing box structure, leading and trailing edge structure and leading and trailing edge control surfaces. Actuation for the control surfaces is accounted for in the flight controls system. The wing carry through structure is included with the wing system. Systems such as the fuel system, hydraulic system and anti-ice system are included with their respective functional systems. For wing mounted landing gear designs, the wing bulkhead, trunnion attach fitting and auxiliary spar structure required to distribute landing gear loads in the wing and to transfer these loads to the fuselage are included with the alighting gear system. All wing attach bulkheads located in the fuselage are included in the body system.

The tail system or empennage is defined similar to that of the wing. The horizontal tail includes all carry through structure, but the vertical tail usually terminates at the fuselage loft line (top of fuselage). Fairings, fillets and the fin are included with the tail system.

The body system consists of fuselage shell structure, door and window frames, doors, windows, floors, bulkheads, cockpit windshield, radome, and tailcone. Door actuation mechanisms and airstairs are also included with the body system. For the C-5A and AST(M), the body system includes the cargo loading system since it is built in integral with the floor structure. Sidewall insulation and paneling as well as cockpit instrument panels and consoles are considered part of the furnishings and equipment system.

B. ALIGHTING GEAR SYSTEM

The alighting gear system consists of all items associated with main and nose gears. This includes landing gear structure which is made up of struts, side and drag braces, bogie beams and/or axles, trunnions, attachment fittings and wing attachment bulkheads, and extra load-path material in the wing for wing mounted gears. The alighting gear controls comprise the components for such functions as retraction, braking and steering. The controls also include cables, wires, or lines from the cockpit controls to the landing gear. In addition, the alighting gear system includes the rolling items of wheels, brakes and tires.

C. NACELLE SYSTEM

The nacelle system includes the cowl structure, the pylon structure, and the sound suppression rings and supports. In general, the cowl represents the structure from the inlet to the engine rear face excluding the thrust reverser structure. The exhaust duct, aft cowling and thrust reverser structure aft of the engine rear face is included with the propulsion system. The fan thrust reverser including inner and outer ducting and core cowl over the length of the fan thrust reverser is also included with the propulsion system.

The pylon includes the apron, engine mounts and wing or fuselage attach fittings. Wing or fuselage attach bulkheads are included with their respective functional systems.

The sound suppression components include the rings and support struts. Any sound suppression treatment to the cowl inside walls is included with the cowl. Any inner skin and ducting for ice protection in the sound suppression rings and nacelle inlet lip are included with the anti-icing system.

D. PROPULSION SYSTEM (LESS ENGINE)

The propulsion system includes the engines (which are not considered in this study), the fan exhaust thrust reverser system, the engine exhaust thrust reverser/spoiler system, the engine system and fuel system. The fan exhaust thrust reverser system includes the translating structure, cascades, blocker doors, fan exhaust ducting located with the translating structure and the actuation system and controls. The engine exhaust thrust reverser/spoiler system includes all of the structure and systems located aft of the engine turbine exhaust flange which include the thrust reverser, tailpipe and bullet. The engine systems include components for cooling, lubrication, ignition, throttle and starting as well as the water injection system and cockpit controls. The fuel system includes the fuel fill and drain system, fuel distribution system, fuel vent plumbing, fuel dump system, integral wing tank sealant and supplemental fuel tanks.

E. FLIGHT CONTROLS SYSTEM

The flight controls system includes the following components: cockpit controls, mechanical controls, hydraulic controls (actuators, control valves, plumbing and fluid), control surface dampers, electrical controls (except the integrated flight guidance and controls), and miscellaneous supports, fairleads, rub strips and attachments. Military Standard 1374 also includes the autopilot in the flight control system. But, in some of the recent transport aircraft, it is difficult to separate the autopilot system from the flight guidance and control system because of the interdependency among components. Therefore, in this study the autopilot system is included with the integrated flight guidance and control system which is part of the avionics system.

Flight control functions may be broken into two groups: those performed by the primary flight controls and those performed by the secondary flight controls. Primary flight controls consist essentially of controls for the horizontal stabilizer, rudder, ailerons and spoilers. These provide pitch, roll and yaw control on all three axes. The secondary flight control system provides for symmetrical operation of wing leading edge slats and trailing edge flaps. This action provides lift augmentation for aircraft takeoff and landing.

F. HYDRAULIC SYSTEM

The hydraulic system provides power to operate the alighting gears and the hydraulic flight control components. This system is required to meet peak system demands during the most critical flight and landing conditions. Because of the criticality of its function, it is generally redundant. For example, the L-1011 has four separate, parallel, continuously operating hydraulic systems such that it can complete its flight plan with two inoperative systems and can maintain control and land safely with three inoperative systems.

Engine driven hydraulic pumps are the primary power source for hydraulic systems. These are occasionally supplemented by a pump connected to an air turbine motor for emergency or peak power requirements. Electric motor-driven pumps powered by the auxiliary power unit provide power for low flow ground checkout and preflight pressurization. Power transfer units are one-way motor-driven pumps which provide the capability of generating fluid pressure in one system through pumps driven by hydraulic motors powered by another source. In addition to pumps, the hydraulic system includes reservoirs, accumulators, filters, valves, controls and plumbing.

G. ELECTRICAL SYSTEM

The electrical system supplies power to a variety of operation components on an aircraft including, among others: lights, avionics, instruments, passenger and cargo doors, galleys, environmental control system, fire extinguishers, landing gear controls and auxiliary power unit (APU) starting.

The electrical system consists of the AC power system, DC power system, and lighting system. The AC and DC power systems include power generating equipment (i.e., constant speed drives, generators, and batteries) and the necessary controls, wiring, fittings and supports to distribute the electrical power from the power source to the electrical power center. The AC and DC power systems also include the structure and circuitry of the electrical power center. Circuitry from the power center to the various components using electricity are included with their respective functions.

The lighting system includes all interior and exterior lights with their supports and associated circuitry. For commercial aircraft, the interior lighting system includes the individual passenger reading lights.

H. INTEGRATED PNEUMATIC SYSTEM

Integrated pneumatic system (IPS) is a term often applied to the combined pneumatic, air conditioning, anti-icing and auxiliary power systems. Although these systems are treated separately in Military Standard 1374 (except for the pneumatic system which is combined with the hydraulic system) the manufacturers and their major subcontractors consider them as part of a single system because of their commonality. In some cases an aircraft manufacturer will have a single subcontractor oversee the design and production of all of these systems. The systems which comprise the IPS are discussed below in turn.

Pneumatic System

The pneumatic system includes all heat exchangers and ducting which carries pressurized air from each of the main engines and from the auxiliary power unit (APU). The pneumatic system provides compressed air for cabin pressurization, air conditioning and ventilation, engine starting, ice prevention on critical aerodynamic surfaces, and turbine driven supplementary or emergency hydraulic power. To perform these functions, each turbine engine is equipped with a bleed air extraction system. The bleed air control system regulates the pressure and temperature of air supplied to pneumatic accessories and to the air conditioning system. The pressurized air is distributed by a comprehensive ducting system, suitable pneumatic ground service connections, the necessary control and isolation and check valves.

Anti-Icing System

Anti-icing functions can be performed by either hot bleed air or electrical heat. Bleed air systems, which are the most common, include all ducting from the main pneumatic source and inner skins which form the hot air cavities along the leading edges of the surfaces. Electrical systems include the electrical blankets fastened to the outer surfaces of critical surfaces plus all wiring and controls.

Auxiliary Power Plant System

The auxiliary power plant system supplies all power for ground operations in lieu of ground support equipment. These operations include: cabin ground air conditioning, engine starting, air turbine motor driven hydraulic power and driving a generator for electric power. In addition to allowing ground self-sufficiency, the auxiliary power plant system may be used in flight to provide emergency or supplemental power for air conditioning, hydraulic services and other critical, electrically powered components. When the auxiliary power plant is expected to be operated in flight, FAA regulations require that it be enclosed in a stainless steel housing for fire protection and this enclosure is considered as part of the auxiliary power plant system.

The auxiliary power system includes the auxiliary power unit (APU), fireproof enclosure, air induction and exhaust, piping and auxiliary back-up components such as starter, battery and generator.

I. FURNISHINGS AND EQUIPMENT SYSTEM

Furnishings and equipment include a variety of items in the cockpit main cabin and cargo compartment. In the cockpit, this category includes all instrument and console panels, seats, insulation, lining, crew oxygen system, and cockpit door and partitions.

In the main cabin of the commercial aircraft, this category includes seats, floor covering, insulation, side panels, ceiling structure, hatrack or baggage containers, complete lavatory installation, complete galley installation including food container inserts, ovens, refrigerators, food carts, window shades, divider partitions, stowage provisions for luggage and magazines, passenger cool air and call buttons, stewardess seats, and passenger oxygen system including portable emergency oxygen bottles.

Passenger reading lights are included with the electrical system and discussed with it. The entertainment system is included in the avionics system.

In the cabin of military aircraft, the furnishings and equipment category includes insulation and lining, troop seats, litters, crew bunks, galley and lavatory, floor covering, cargo and aerial delivery system (winches, pry-bar, tie-down fittings), equipment stowage and troop oxygen system.

In the belly of the commercial aircraft, this category includes insulation and lining and belly cargo loading system. The cargo containers are not included as they are operator's items.

Miscellaneous items include the engine and cabin fire extinguisher systems, fire warning system, exterior finish, and miscellaneous emergency equipment (i.e., first aid kit and fire ax). Emergency exit slides and life rafts are not included as they are operator's items.

J. INSTRUMENT SYSTEM

Instruments perform the basic monitoring and warning functions associated with the flight of the aircraft, control surface positioning, electrical, hydraulic and pneumatic systems operation, engine operation, and fuel quantity. The instrument system includes cockpit indicators and warning lights, electronic black boxes at the point of signal input, and circuitry between the black boxes and the monitoring devices.

K. AVIONICS SYSTEM

The avionics system is separated into four subsystems as follows:

1. The integrated flight guidance and controls subsystem includes the autopilot system, and associated pitch, roll, yaw computers; the flight director system; the gyrocompass system; the attitude and heading reference system; and the inertial navigation system. These units are interdependent and are, therefore, integrated into one operating unit. Although a

part of this subsystem, the auto-throttle/thrust management system is included with the propulsion system because it functions as an engine control. All indicators, servomechanism, and associated circuitry, supports and attachments related to the integrated flight guidance and controls subsystem are also included.

2. The communication subsystem is separated by its internal and external functions.

   a. The internal communication system includes the interphone system, the public address system, and the multiplex (MUX) system. The MUX system is a signal transmission source for the passenger-to-attendant call system, passenger entertainment system, the public address system, the reading light system, the passenger oxygen latch release system and the passenger individual cool air system. The DC-10 and the L-1011 utilize a communication MUX system. All amplification units, head and hand sets, speaker installations, encoders and decoders for the MUX system, and associated wiring, supports and attachments related to the internal communication system are also included.

   b. The external communication system includes the radio equipment which is used for aircraft to aircraft or aircraft to ground communications. It is composed of the very high frequency (VHF) system, the high frequency (HF) system, the ultrahigh frequency (UHF) system, provisions for satellite communication, the selective call (SELCA) system, and the voice scrambler system. Most overwater airplanes are equipped with HF or UHF equipment. All radio units, antennas, and associated coax, wiring, supports and attachments related to the external communication system are also included.

3. The navigation subsystem includes all radar equipment, the automatic direction finding (ADF) system, the distance measuring equipment (DME) system, the long range navigation (LORAN) system, the doppler system, the navigation computer systems, the stationkeeping system, the tactical air navigation (TACAN) system, the variable omnirange (VOR) system, the marker beacon system, the instrument landing system (ILS), the collision avoidance system (CAS), the airport traffic control (ATC) system the radio altimeter system, the glide slope system and the radar beacon system. Most overwater aircraft are equipped with LORAN and doppler systems. All of the navigation units, indicators, antennas, associated circuitry and antenna coax, and supports and attachments related to the navigation subsystem are also included.

4. The miscellaneous equipment subsystem includes the flight, voice and crash recorder systems, the aircraft integrated data (AID)/ malfunction detection analysis and recording (MADAR) systems, the weight and balance system, if installed, the equipment rack structure and miscellaneous hardware and circuitry.

L. LOAD AND HANDLING SYSTEM

The load and handling system consists of fittings and structural provisions for jacking, hoisting and mooring. Some military aircraft have stabilizer jacks to hold the aircraft in a rigid position during cargo loading.

REFERENCES

1. Levenson, G.S., et. al., Cost Estimating Relationships for Aircraft Airframes, The RAND Corporation, R-761-PR, December 1971 (Proprietary).

2. Large, J.P., et. al., Parametric Equations for Estimating Aircraft Airframe Costs, The RAND Corporation, R-1693-PA&E, May 1975.

3. Planning Research Corporation, Methodology for Estimating Development, Production, and Operating Costs of Transport Aircraft, PRC R-634, December 1964 (Proprietary).

4. Kenyon, R. E., Weapon System Costing, Methodology for Aircraft Airframes and Basic Structures, General Dynamics Convair Division, AFFDL-TR-75-44, June 1975.

5. C-5 Cost, Schedule, and Technical Characteristics Study, Lockheed Georgia Company MSC 07018, November 1972.

6. Trapp, Donald, Fernando Heyer, Bruce Kimoto, Daniel Marsh, Parametric Study of Transport Aircraft Systems Weight and Cost, PRC System Sciences Company, October 1974 (Proprietary Information - Distribution Limited).

7. York, Roy A. Flight Weight Actuators An Evaluation of the Weight of Aircraft Hydraulic Actuators, Presented Before the Seventy-third Meeting of the Society of Automotive Engineers.

8. Boren, H. E., and H. G. Campbell, Learning Curve Tables, RM-6191 PR, The RAND Corporation, April 1970.

9. Teng, C., An Estimating Relationship for Fighter/Interceptor Avionics System Procurement Cost, The RAND Corporation, May 1966.

10. Frank Cherry, (Air Force Materials Laboratory) Composites Technology - Threshold to Low Cost Aircraft Structures, AIAA Paper No. 75-1306, August, 1975.

11. Douglas Aircraft Company, Study of the Quiet Turbofan STOL Aircraft for Short Haul Transportation Final Report Volume V Economics, NASA CR-114610, June 1973.

12. Nordstrom, Kenneth E., Alan H. Marsh, Donald F. Sargisson, Conceptual Design Study of Advanced Acoustic Composite Nacelles, NASA CR-132763, Douglas Aircraft Company, July 1975.

13. Anderson, Joseph L., A Parametric Determination of Transport Aircraft Price, SAWE Paper No. 1071, May 5-7, 1975.

14. Committee on Implementation of Cost Saving Recommendations for Aerospace Construction, Aerospace Cost Savings - Implications for NASA and the Industry, NAMB-326, National Materials Advisory Board, 1975.

15. Lockheed-California Company and Lockheed-Georgia Comp [illegible] iet Turbofan STOL Aircraft for Short Haul Transportation, Final Repo [illegible] NASA CR 114612, 14 June 1973.

16. Kenyon, R. E., Techniques for Estimating Weapon System Structural Costs Technical Report AFFDL-TR-71-74, Convair Aerospace Division of General Dynamics, July 1971.

REFERENCES (CONTINUED)

17. Douglas Aircraft Company, Mass Properties Report - Advanced STOL Transport (Medium), Report MDC-J5652, 14 August 1972.

18. Douglas Aircraft Company, Study of Quiet Turbofan STOL Aircraft for Short-Haul Transportation, Report NASA CR-114607, June 1973.